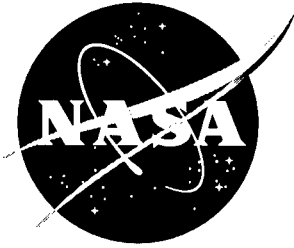


Solution of the Angles-Only Satellite Tracking Problem

R.E. Burns



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TECHNICAL PAPER

SOLUTION OF THE ANGLES-ONLY SATELLITE TRACKING PROBLEM

INTRODUCTION

The determination of the orbit of a satellite vehicle or ballistic missile is obviously of great practical importance. In the usual case, the azimuth, elevation, range, and range-rate of the target are measured from an Earth-fixed radar site. When range and range-rate are not available, the determination of the orbit from the azimuth(s), elevation(s), and the time(s) of the observation is referred to as the "angles-only problem."

A good summary of this problem is treated in reference 1. In that source, it is pointed out that the problem was solved by Gauss, Laplace, and Escobal. These solutions seem to be far better known among astronomers than among aerospace engineers.*

In the present report, another solution is derived which is particularly well suited to numerical calculations. It is shown that all of the orbital elements (semi-major axis (a), eccentricity (e), argument of perigee ($\tilde{\omega}$), inclination (I), and longitude of the ascending node (Ω)) can be derived from five measurements of the azimuth (and the times of observation), or five measurements of the elevation (and the times of observation). Once these elements have been isolated, the epoch can be derived from a given time measurement.

An advantage of the present formulation is that it can be readily extended to the case of an observer aboard a second satellite rather than an Earth-fixed observer. Since only line-of-sight angles would be required to determine the orbit of a second satellite, the technique could be used to eliminate range and range-rate hardware that is presently required for rendezvous. This option will be treated in a future paper.

THE DRIVER PROGRAM

In the case of an actual radar installation, the azimuth and elevation angles, as well as the time of the observations, would be recorded once a target is acquired. Since this report deals with theoretical sightings rather than actual observations, it is necessary to build a driver program to simulate what a real radar station would observe. To that end, a vehicle having arbitrary orbital elements is assumed and the details of the sightings from a general configuration are derived. From a general configuration, specific orbital elements are used for simulation. Once the elevation, azimuth, and time are calculated, the orbital parameters are hidden from the isolation scheme. The isolation then has to rederive a complete specification of the orbit from the table of elevation angle versus time (or the azimuth versus time). Since a ballistic missile that impacts the Earth is obviously in a "terminated" orbit, the same theory applies in either case, i.e., one can track an incoming missile using the present theory. For the ballistic missile case, drag would be a significant factor, however. Drag is not included in the present report.

* The author wishes to thank Dr. John Hanson, EL-58, MSFC, for pointing out this literature on this subject.

Let $(\hat{i}, \hat{j}, \hat{k})$ describe an Earth-centered inertial coordinate system and locate a tracking station by the polar coordinates (R_o, ϕ_o, θ_o) (fig. 1). We explicitly recognize the Earth's rotation by setting $\phi_o = \phi_o(t)$. At the tracking station, a spherical coordinate system is constructed via the unit vectors $(\hat{u}_r, \hat{u}_\theta, \hat{u}_\phi)$. Note that this coordinate system is modified from the usual convention in that the \hat{u}_θ points due south along the meridian rather than the conventional practice of orienting it to the north. The target is located, relative to the tracking station by a distance, ρ , and two angles, the azimuth α , and the elevation angle, β .

The unit vector transformation is:

$$\hat{u}_r = \cos \theta_o \cdot \cos \phi_o \cdot \hat{i} + \cos \theta_o \cdot \sin \phi_o \cdot \hat{j} + \sin \theta_o \cdot \hat{k},$$

$$\hat{u}_\phi = \sin \phi_o \cdot \hat{i} + \cos \phi_o \cdot \hat{j},$$

$$\hat{u}_\theta = \sin \theta_o \cdot \cos \phi_o \cdot \hat{i} + \sin \theta_o \cdot \sin \phi_o \cdot \hat{j} - \cos \theta_o \cdot \hat{k},$$

along with the vector from the center of the Earth to the radar station, \vec{R}_o , as

$$\vec{R}_o = R_o \cdot \cos \theta_o \cdot \cos \phi_o \cdot \hat{i} + R_o \cdot \cos \theta_o \cdot \sin \phi_o \cdot \hat{j} + R_o \cdot \sin \theta_o \cdot \hat{k}, \quad (1)$$

where $R_o = |\vec{R}_o|$.

In the local coordinates of the radar station, the ρ vector is given by

$$\vec{\rho} = \rho \cdot (\sin \beta \cdot \hat{u}_r + \cos \beta \cdot \sin \alpha \cdot \hat{u}_\phi + \cos \beta \cdot \cos \alpha \cdot \hat{u}_\theta), \quad (2)$$

where $\rho = |\vec{\rho}|$.

Inserting the expressions for \hat{u}_r , \hat{u}_ϕ , and \hat{u}_θ into the expressions for $\vec{\rho}$, one finds

$$\begin{aligned} \vec{\rho} = \rho \cdot [& (\sin \beta \cdot \cos \theta_o \cdot \cos \phi_o - \cos \beta \cdot \sin \alpha \cdot \sin \phi_o + \cos \beta \cdot \cos \alpha \cdot \sin \theta_o \cdot \cos \phi_o) \cdot \hat{i} \\ & + (\sin \beta \cdot \cos \theta_o \cdot \sin \phi_o + \cos \beta \cdot \sin \alpha \cdot \cos \phi_o + \cos \beta \cdot \cos \alpha \cdot \sin \theta_o \cdot \sin \phi_o) \cdot \hat{j} \\ & + (\sin \beta \cdot \sin \theta_o - \cos \beta \cdot \cos \alpha \cdot \cos \theta_o) \cdot \hat{k}] . \end{aligned} \quad (3)$$

Define a vector \vec{r} from the center of the Earth to the satellite. For reference 2, one can write \vec{r} in terms of the inclination, I , the right ascension of the ascending node, Ω , the argument of perigee, ω , and the true anomaly, f , as

$$\begin{aligned} \vec{r} = x \cdot \hat{i} + y \cdot \hat{j} + z \cdot \hat{k} = r \cdot [& \cos(f + \tilde{\omega}) \cdot \cos \Omega - \sin(f + \tilde{\omega}) \cdot \sin \Omega \cdot \cos I] \cdot \hat{i} \\ & + r \cdot [\cos(f + \tilde{\omega}) \cdot \sin \Omega + \sin(f + \tilde{\omega}) \cdot \cos \Omega \cdot \cos I] \cdot \hat{j} \\ & + r \cdot \sin(f + \tilde{\omega}) \cdot \sin I \cdot \hat{k} , \end{aligned} \quad (4)$$

where $r = |\vec{r}|$ (see fig. 2). Also, one can write

$$r = a \cdot (1 - e^2) / (1 + e \cdot \cos f) = p / (1 + e \cdot \cos f), \quad (5)$$

where a is the semi-major axis of the orbit and e as the eccentricity and $p = a \cdot (1-e^2)$.

Vectorially,

$$\vec{r} = \vec{R}_o + \vec{\rho} . \quad (6)$$

Equating the components of equation (6) from equations (5), (3), and (1),

$$\begin{aligned} \rho \cdot (\sin \beta \cdot \cos \theta_o \cdot \cos \phi_o - \cos \beta \cdot \sin \alpha \cdot \sin \phi_o + \cos \beta \cdot \cos \alpha \cdot \sin \theta_o \cdot \cos \phi_o) \\ = r \cdot [\cos (f+\tilde{\omega}) \cdot \cos \delta\mathcal{L} - \sin (f+\tilde{\omega}) \cdot \sin \delta\mathcal{L} \cdot \cos I] - R_o \cdot \cos \theta_o \cdot \cos \phi_o , \end{aligned} \quad (7)$$

$$\begin{aligned} \rho \cdot (\sin \beta \cdot \cos \theta_o \cdot \sin \phi_o + \cos \beta \cdot \sin \alpha \cdot \cos \phi_o + \cos \beta \cdot \cos \alpha \cdot \sin \theta_o \cdot \sin \phi_o) \\ = r \cdot [\cos (f+\tilde{\omega}) \cdot \sin \delta\mathcal{L} + \sin (f+\tilde{\omega}) \cdot \cos \delta\mathcal{L} \cdot \cos I] - R_o \cdot \cos \theta_o \cdot \sin \phi_o , \end{aligned} \quad (8)$$

$$\rho \cdot (\sin \beta \cdot \sin \theta_o - \cos \beta \cdot \cos \alpha \cdot \cos \theta_o) = r \cdot \sin (f+\tilde{\omega}) \cdot \sin I - R_o \cdot \sin \theta_o . \quad (9)$$

Taking the square root of the sum of the squares of equations (7), (8), and (9) gives

$$\begin{aligned} \rho = \langle r^2 + R_o^2 - 2 \cdot r \cdot R_o \cdot \{ [\cos (f+\tilde{\omega}) \cdot \cos \theta_o \cdot \cos (\delta\mathcal{L} - \phi_o) - \sin (f+\tilde{\omega}) \cdot \cos \theta_o \cdot \cos I \cdot \sin (\delta\mathcal{L} - \phi_o) \\ - \sin I \cdot \sin \theta_o] \} \rangle^{1/2} . \end{aligned} \quad (10)$$

Although the preceding equations can be solved directly for α and β , a more subtle approach yields additional quadrant information that can be valuable during numerical calculations. To this end, one first calculates $(8) \cdot \cos \phi_o - (7) \cdot \sin \phi_o$ to get

$$\rho \cdot \cos \beta \cdot \sin \alpha = r \cdot [\cos (f+\tilde{\omega}) \cdot \sin (\delta\mathcal{L} - \phi_o) + \sin (f+\tilde{\omega}) \cdot \cos I \cdot \cos (\delta\mathcal{L} - \phi_o)] . \quad (11)$$

Next, calculate $(7) \cdot \cos \phi_o + (8) \cdot \sin \phi_o$ to yield

$$\begin{aligned} \rho \cdot (\sin \beta \cdot \cos \theta_o + \cos \beta \cdot \cos \alpha \cdot \sin \theta_o) \\ = r \cdot [\cos (f+\tilde{\omega}) \cdot \cos (\delta\mathcal{L} - \phi_o) - \sin (f+\tilde{\omega}) \cdot \cos I \cdot \sin (\delta\mathcal{L} - \phi_o) - R_o \cos \theta_o] . \end{aligned} \quad (12)$$

From $(12) \cdot \sin \theta_o - (9) \cdot \cos \theta_o$ one has

$$\begin{aligned} \rho \cdot \cos \beta \cdot \cos \alpha = r \cdot \{ \cos (f+\tilde{\omega}) \cdot \cos (\delta\mathcal{L} - \phi_o) \cdot \sin \theta_o \\ - \sin (f+\tilde{\omega}) \cdot [\cos I \cdot \sin (\delta\mathcal{L} - \phi_o) \cdot \sin \theta_o + \sin I \cdot \cos \theta_o] \} . \end{aligned} \quad (13)$$

Now, divide equation (11) by equation (13) and obtain the formula for the tangent of α as

$$\begin{aligned} \tan \alpha = [\cos (f+\tilde{\omega}) \cdot \sin (\delta\mathcal{L} - \phi_o) + \sin (f+\tilde{\omega}) \cdot \cos I \cdot \cos (\delta\mathcal{L} - \phi_o)] / \{ \cos (f+\tilde{\omega}) \cdot \cos (\delta\mathcal{L} - \phi_o) \cdot \sin \theta_o \\ - \sin (f+\tilde{\omega}) \cdot [\cos I \cdot \sin (\delta\mathcal{L} - \phi_o) \cdot \sin \theta_o + \sin I \cdot \cos \theta_o] \} . \end{aligned} \quad (14)$$

Equation (14) may be rewritten in many forms, with one of the more useful being

$$\tan \alpha = [\sin (\delta\mathcal{L}-\phi_o) + \tan (f+\tilde{\omega}) \cdot \cos I \cdot \cos (\delta\mathcal{L}-\phi_o)] / \{ \cos \theta_o \cdot [\cos (\delta\mathcal{L}-\phi_o) \cdot \tan \theta_o - \tan (f+\tilde{\omega}) \cdot [\cos I \cdot \sin (\delta\mathcal{L}-\phi_o) \cdot \tan \theta_o + \sin I]] \} . \quad (15)$$

In equation (14), one can separately interrogate the numerator and denominator (interpreted as $\sin \alpha$ and $\cos \alpha$) to obtain the needed quadrant information on α .[†]

The elevation, β , can be obtained in several ways. One such method would come from multiplying equation (12) by $\cos \theta_o$ and equation (9) by $\sin \theta_o$ and adding to obtain

$$\rho \cdot \sin \beta = r \cdot \{ \cos (f+\tilde{\omega}) \cdot \cos (\delta\mathcal{L}-\phi_o) \cdot \cos \theta_o - \sin (f+\tilde{\omega}) \cdot [\cos I \cdot \sin (\delta\mathcal{L}-\phi_o) \cdot \cos \theta_o - \sin I \cdot \sin \theta_o] \} - R_o . \quad (16)$$

Squaring and adding equations (11) and (13) yields a formula for $\cos \beta$, but this process destroys information. Dividing equation (15) by that equation for $\cos \beta$ will yield a tangent formula which involves r and R_o but not ρ .

Another approach to determine β is simply to utilize equation (10) to determine ρ and then use either equation (11) or equation (13) to obtain β as an arc cosine. Equation (11) would be greatly preferred since $\cos \alpha$ will usually vanish during a satellite pass.

The magnitude of the radius vector, r , which appears in many of the above equations involves the semi-major axis, a , and the eccentricity, e . If one has full knowledge of the orbital elements a , e , I , ϖ , and $\delta\mathcal{L}$, and if one also knows the epoch (or a related time point), one can now obtain the values of ρ , α , and β . The time reference serves to determine the true anomaly, f , and the position of the observation site, since $\phi_o = \phi_o(t)$.

For given values of the orbital elements and epoch (needed for r and ϕ_o), the path of computation is now clear. Equation (10) yields the values of ρ , and equation (15) can be solved for α . Once ρ and α are known, equation (11) provides the value of β .

It is apparent that not all values of the epoch will yield values of (ρ, α, β) which correspond to physical data that could be recorded at a given observation site. Subsidiary conditions must be imposed on the epoch (as well as on θ_o) in order to guarantee that the satellite is above the horizon of a ground plane which is tangent to the site. ("Over the horizon radar" is not considered here, but such a device could easily be incorporated into these equations.) Physically, apparition of the target is expected when $\beta = 0$ and occultation when $\beta = \pi$. These conditions will be fulfilled if

$$\vec{\rho} \cdot \vec{R}_o = 0 .$$

Dotting equation (1) with equation (3) gives

$$\cos (f+\tilde{\omega}) \cdot \cos (\delta\mathcal{L}-\phi_o) \cdot \cos \theta_o - \sin (f+\tilde{\omega}) \cdot [\cos I \cdot \sin (\delta\mathcal{L}-\phi_o) \cdot \cos \theta_o - \sin I \cdot \sin \theta_o] = R_o / r . \quad (17)$$

This equation is time dependent through the variables f , r , and ϕ_o . In order to recognize the explicit time dependence of the longitude of the observation site, write

$$\phi_o \rightarrow \phi_o + \dot{\phi} \cdot t . \quad (18)$$

[†] The author wishes to thank Dr. Larry Mullins, MSFC, NASA, for pointing out the existence of this formula.

Since the true anomaly, f , is time dependent, r must be expanded by equation (5). In terms of the eccentric anomaly, \mathcal{E} ,

$$r = a \cdot [1 - e \cdot \cos(\mathcal{E})]. \quad (19)$$

The eccentric anomaly is related to the time by Gauss' equation (zero referenced to the time of perigee passage) as

$$t = \sqrt{(a^3/\mu)} \cdot (\mathcal{E} - e \cdot \sin \mathcal{E}), \quad (20)$$

and to the true anomaly, f , via

$$f = 2 \cdot \tan^{-1} \{ \sqrt{[(1+e)/(1-e)]} \cdot [\tan(\mathcal{E}/2)] \}. \quad (21)$$

Since we are in the driver program, it is assumed that the orbital elements are all known. One must isolate a value of the time such that equation (17) is satisfied, along with equations (18) through (21). Since no useful analytic solution exists even for equation (20), there is little hope of solving equation (17) analytically. For this reason, a Newton iteration was developed that defined

$$H = \cos(f + \tilde{\omega}) \cdot \cos(\delta\mathcal{L} - \phi_o) \cdot \cos \theta_o - \sin(f + \tilde{\omega}) \cdot [\cos I \cdot \sin(\delta\mathcal{L} - \phi_o) \cdot \cos \theta_o - \sin I \cdot \sin \theta_o] - R_o/r, \quad (22)$$

in accord with equation (17). To isolate a zero of H , the iterator requires that one also know $\partial H/\partial t$.

$$\begin{aligned} \partial H/\partial t = & -\{ \sin(f + \tilde{\omega}) \cdot \cos(\delta\mathcal{L} - \phi_o) \cdot \cos \theta_o + \cos(f + \tilde{\omega}) \cdot [\cos I \cdot \sin(\delta\mathcal{L} - \phi_o) \cdot \cos \theta_o \\ & - \sin I \cdot \sin \theta_o] \} \cdot \sqrt{(p \cdot \mu)/r^2} - \{ \cos(f + \tilde{\omega}) \cdot \sin(\delta\mathcal{L} - \phi_o) \cdot \cos \theta_o \\ & + \sin(f + \tilde{\omega}) \cdot [\cos I \cdot \cos(\delta\mathcal{L} - \phi_o) \cdot \cos \theta_o] \} \cdot \dot{\phi} + (R_o/p) \cdot e \cdot \sin f \cdot \sqrt{(p \cdot \mu)/r^2}, \end{aligned} \quad (23)$$

where

$$\partial f/\partial t = \sqrt{[\mu \cdot a \cdot (1 - e^2)]/r^2} = \sqrt{(p \cdot \mu)/r^2},$$

and

$$\partial/\partial t(1/r) = -(e/p) \cdot \sin f \cdot \sqrt{(p \cdot \mu)/r^2}$$

have been used.

Although the use of equations (22) and (23) can isolate the apparition and occultation of the target, it is convenient to employ approximate calculations to estimate those times as starting values for the Newton iteration. This can be conveniently done if one assumes (here) that ϕ is zero, but allow f to vary in accord with Keplerian dynamics.

To approximate the apparition and occultation of the target, from equation (13), one defines

$$X_0 = \cos(\delta\mathcal{L} - \phi_o) \cdot \cos \theta_o, \quad (24)$$

$$X_1 = [\cos I \cdot \sin(\delta\mathcal{L} - \phi_o) \cdot \cos \theta_o - \sin I \cdot \sin \theta_o], \quad (25)$$

so that equation (13) can be written as

$$X_0 \cdot \cos(f + \tilde{\omega}) - X_1 \cdot \sin(f + \tilde{\omega}) - R_o/r = 0. \quad (26)$$

Expanding the double angle formulas in equation (22), and abbreviating

$$X_2 = X_0 \cdot \cos \varpi - X_1 \cdot \sin \varpi, \quad (27)$$

$$X_3 = X_0 \cdot \sin \varpi + X_1 \cdot \cos \varpi, \quad (28)$$

allows equation (22) to be written as

$$X_2 \cdot \cos f - X_3 \cdot \sin f - R_o/r = 0. \quad (29)$$

Inserting r from equation (5) into equation (29) and cross multiplying by the denominator of r gives

$$\cos f \cdot (X_2 - R_o \cdot e/p) - \sin f \cdot X_3 = R_o \cdot e/p. \quad (30)$$

Defining the variable η by

$$\eta = \tan^{-1} [X_3 / (X_2 - R_o \cdot e/p)], \quad (31)$$

and ξ as

$$\xi = \cos^{-1} \langle R_o \cdot e / \{ p \cdot \sqrt{[X_3^2 + (X_2 - R_o \cdot e/p)^2]} \} \rangle, \quad (32)$$

allows one to write equation (30) as

$$\cos (f + \eta) = \cos \xi. \quad (33)$$

Equation (29) has two solutions, either

$$f = \xi - \eta, \quad (34)$$

or

$$f = 2\pi - (\xi + \eta). \quad (35)$$

Either the solution of equation (34) or the solution of equation (35) will correspond to apparition on a nonrotating Earth; the other will correspond to occultation. Although Gauss' equation assumes that the initial time point occurs at perigee, it is not difficult to introduce a false time reference of zero at apparition by defining this point as t_o and then writing all time values, t , as $t - t_o$. Once the time of apparition has been isolated, this time can be used as a starting point for the equations since the calculation starts at that instant. The second solution for f (which could be the solution of either equation (34) or (35)) then supplies a starting value for the Newton iteration of equation (22) so that the method will converge on occultation rather than apparition.

An orbital table can now be produced by choosing an arbitrary number of points between the f_o (apparition) and the f_f (occultation). Since each f and the orbital elements are known, one can specify all the orbital parameters at these points. Table 1 shows the results of such a procedure for 15 points on a typical orbit. The orbital elements were arbitrarily taken as $a = 7,420$ km, $e = 0.1$, $\varpi = 25^\circ$, $I = 35^\circ$, and $\delta_L = 33^\circ$; ϕ_o was taken as 77° and θ_o as 28.5° , and the Earth's rotation rate, ϕ , was $2\pi/(24 \cdot 3,600)$. Apparition occurred at $f_o = 8.481^\circ$ (122.153 seconds past perigee), and occultation occurred at $f_f = 50.855^\circ$ (749.288 seconds past perigee). The remaining entries of table 1 were calculated by the use

of equations (5) for r , (10) for ρ , (15) for α , and (11) for β . \mathcal{E} can most easily be obtained from equation (19). The equations that were used to compute the values of the orbital angles ϕ and θ are from standard celestial mechanics

$$\phi = \tan^{-1} \{ [\tan (f+\tilde{\omega}) \cdot \cos I + \tan \delta \mathcal{L}] / [1 - \tan (f+\tilde{\omega}) \cdot \cos I \cdot \tan \delta \mathcal{L}] \} , \quad (36)$$

and

$$\theta = \tan^{-1} [\tan I \cdot \sin (\phi - \delta \mathcal{L})] . \quad (37)$$

It is interesting to determine how large β can become in the field of view. This can be done by requiring that $\partial\beta/\partial f = 0$, and then solving for the corresponding value of f . When this value of f is inserted into equation (11), the maximum value of β will be found. If one uses equation (11), that procedure is algebraically rather messy. It is better to proceed by abbreviating

$$X = \cos (f+\tilde{\omega}) \cdot \cos (\delta \mathcal{L} - \phi_o) \cdot \cos \theta_o - \sin (f+\tilde{\omega}) \cdot [\cos I \cdot \sin (\delta \mathcal{L} - \phi_o) \cdot \cos \theta_o - \sin I \cdot \sin \theta_o] , \quad (38)$$

so that equations (10) and (11) can be written, respectively as

$$\rho = \sqrt{(r^2 + R_o^2 - 2 \cdot r \cdot R_o \cdot X)} , \quad (39)$$

$$\sin \beta = (r \cdot X - R_o) / \rho = (r \cdot X - R_o) / \sqrt{(r^2 + R_o^2 - 2 \cdot r \cdot R_o \cdot X)} , \quad (40)$$

which immediately yields

$$\tan \beta = (r \cdot X - R_o) / [r \cdot \sqrt{(1 - X^2)}] . \quad (41)$$

If we now take the derivative of (41), equate $\partial\beta/\partial f$ to zero and clear, we find that the requirement for β to be a maximum is

$$R_o \cdot (1 - X^2) \cdot (\partial r / \partial f) + r \cdot [r - R_o \cdot X] \cdot (\partial X / \partial f) = 0 . \quad (42)$$

From equation (15), we have

$$\partial r / \partial f = r^2 e \cdot \sin f / p , \quad (43)$$

while equation (34) gives

$$\begin{aligned} \partial X / \partial f = & -\sin (f+\tilde{\omega}) \cdot \cos (\delta \mathcal{L} - \phi_o) \cdot \cos \theta_o - \cos (f+\tilde{\omega}) \cdot [\cos I \cdot \sin (\delta \mathcal{L} - \phi_o) \cdot \cos \theta_o \\ & - \sin I \cdot \sin \theta_o] . \end{aligned} \quad (44)$$

Taking (34) $\cdot \cos (f+\tilde{\omega}) - (44) \cdot \sin (f+\tilde{\omega})$ gives an equation which can be solved for $\partial X / \partial f$ as

$$\partial X / \partial f = X \cdot \cot (f+\tilde{\omega}) - \cos (\delta \mathcal{L} - \phi_o) \cdot \cos \theta_o \cdot \csc (f+\tilde{\omega}) . \quad (45)$$

Inserting equations (15), (43), and (45) into (42) gives, finally,

$$\begin{aligned} X^2 \cdot [e \cdot \cos \tilde{\omega} + \cos (f+\tilde{\omega})] - X \cdot [\cos (\delta \mathcal{L} - \phi_o) \cdot \cos \theta_o \cdot (1 + e \cdot \cos f) + (p/R_o) \cdot \cos (f+\tilde{\omega})] \\ + [(p/R_o) \cdot \cos (\delta \mathcal{L} - \phi_o) \cdot \cos \theta_o + e \cdot \sin f \cdot \sin (f+\tilde{\omega})] = 0 . \end{aligned} \quad (46)$$

Equation (46) is cubic in the trigonometric functions of f . Even if one substitutes $\sin^2 f \rightarrow 1 - \cos^2 f$, the residual $\sin f$ terms will require an additional squaring operation, so the best that we can hope for is a sixth order equation in $\cos f$. This virtually precludes an analytical solution for f , but numerical iteration works very well. For a numerical iteration, it is easier to use equation (42) (along with equations (38), (43), and (44)) rather than equation (46) (along with equation (38)). Once f has been isolated, the maximum value of β can be obtained from equation (41).

A far easier question is to determine whether or not $\beta = \pi/2$ in the viewing field. From equation (41), β can be $\pi/2$ only if $X = \pm 1$. Using equation (38), this requirement implies that

$$\begin{aligned} & \cos(f+\tilde{\omega}) \cdot \cos \theta_o \cdot \cos(\delta\mathcal{L}-\phi_o) - \sin(f+\tilde{\omega}) \cdot [\cos \theta_o \cdot \cos I \cdot \sin(\delta\mathcal{L}-\phi_o) \\ & - \sin I \cdot \sin \theta_o] = \pm 1. \end{aligned} \quad (47)$$

Setting

$$\begin{aligned} \tan \lambda &= [\cos \theta_o \cdot \cos I \cdot \sin(\delta\mathcal{L}-\phi_o) - \sin I \cdot \sin \theta_o] / [\cos \theta_o \cdot \cos(\delta\mathcal{L}-\phi_o)] \\ &= \cos I \cdot \tan(\delta\mathcal{L}-\phi_o) - \sin I \cdot \tan \theta_o \cdot \sec(\delta\mathcal{L}-\phi_o), \end{aligned} \quad (48)$$

then, using spherical trigonometry,

$$\tan \lambda = \cos I \cdot \tan(\delta\mathcal{L}-\phi_o) + \sin I \cdot \tan I \cdot \tan(\delta\mathcal{L}-\phi_o) = \tan(\delta\mathcal{L}-\phi_o) \cdot \sec I. \quad (49)$$

Equation (47) can now be written as

$$\cos(f+\tilde{\omega}) \cdot \cos \lambda - \sin(f+\tilde{\omega}) \cdot \sin \lambda = \pm 1,$$

or

$$\cos(f+\tilde{\omega}+\lambda) = \pm 1. \quad (50)$$

Thus, β will achieve an angle of $\pi/2$ (or $3\pi/2$) if either of the true anomalies

$$f = -\tan^{-1} [\tan(\delta\mathcal{L}-\phi_o) \cdot \sec I] - \tilde{\omega}, \quad (51)$$

or

$$f = \pi - \tan^{-1} [\tan(\delta\mathcal{L}-\phi_o) \cdot \sec I] - \tilde{\omega}, \quad (52)$$

fall between apparition and occultation.

From equation (14), an additional datum is available. It is interesting to determine the value of the true anomaly, f , which results in $\alpha = 0$. For this condition, equation (14) requires that

$$\sin(\delta\mathcal{L}-\phi_o) + \tan(f+\tilde{\omega}) \cdot \cos I \cdot \cos(\delta\mathcal{L}-\phi_o) = 0,$$

or

$$\tan(f+\tilde{\omega}) = -\sec I \cdot \tan(\delta\mathcal{L}-\phi_o). \quad (53)$$

If ϕ is now taken to be the longitude of the satellite (as opposed ϕ_o , the longitude of the tracking station) a standard equation from celestial mechanics gives

$$\tan(f+\tilde{\omega}) = -\sec I \cdot \tan(\delta\mathcal{L}-\phi). \quad (54)$$

For equations (52) and (53) to hold simultaneously, one must then have $\phi = \phi_o$ as the condition for $\alpha = 0$. At this time

$$f = -\{\tan^{-1} [\sec I \cdot \tan (\delta\ell - \phi_o)] + \tilde{\omega}\} . \quad (55)$$

If the satellite was observed exactly at $\alpha = 0$ (and the associated time), it would be possible to use this datum to eliminate one orbital element in terms of the remaining four. However, nonlinearities probably make such a procedure more trouble than it is worth.

THE SOLUTION OF THE ANGLES-ONLY PROBLEM

In order to obtain the data in table 1, it was assumed that the orbital elements were known, but that assumption was used only to simulate data that could be recorded by an observer with full knowledge of the orbit. A naive observer who is located at a radar station and restricted to measuring only elevation and azimuth angles (as well as the time of the observations) could record only the sort of information shown in table 2. The "angles only" problem can now be stated quantitatively as follows: given the five sets of readings in table 2, isolate the five orbital elements, a , e , $\tilde{\omega}$, I , and $\delta\ell$ that could have produced those readings. It will be shown that all of the data of that table are not needed. Indeed, one can isolate the required orbital elements from the five reading of either α and the time or β and the time. But listing α and β and the time is redundant. In practice, since all of the reading will be noisy, it would be prudent to solve the problem twice, with one solution involving α and the other solution involving β and then to compare the two answers. Although only five readings can be used to produce the results, these five readings are mathematically precise and thus are "safe." In actual field work, one would probably take many more readings and compute the elements of the orbits from many sets of five, then statistically validate the final answers. These considerations will not be pursued in the present report.

To begin, assume any convenient set of values for a , e , $\tilde{\omega}$, I , and $\delta\ell$. It is required only that they be reasonable. In most cases, some guess can be made about the semi-major axis (for a satellite, require that $a \cdot (1+e) > R_o$), the eccentricity (say $0 \leq e < 1$) and the inclination (if the observation station is at θ_o , $I \geq \theta_o$).

One could proceed in the calculations in the following way. Once a set of orbital elements have been assumed, one can obtain a value of \mathcal{E} from equation (20) for a given time. Equation (21) then produces the corresponding value of f . Once f has been calculated, obtain ρ from equation (10) and α from equation (15). Equation (11) then gives the value of β . If the guesses about the orbital elements are exact, then the recorded tabular values of α and β will agree with the calculated values of these variables and the problem is solved.

Another procedure was found to be more convenient, however. Given a starting set of guesses (a , e , $\tilde{\omega}$, I , $\delta\ell$), first calculate X_0, \dots, X_3 from equations (26) through (28). Additionally, calculate the following convenient quantities:

$$X_4 = \sin (\delta\ell - \phi_o) , \quad (56)$$

$$X_5 = \cos I \cdot \cos (\delta\ell - \phi_o) , \quad (57)$$

$$X_6 = X_4 \cdot \cos \tilde{\omega} + X_5 \cdot \sin \tilde{\omega} , \quad (58)$$

$$X_7 = X_4 \cdot \sin \tilde{\omega} - X_5 \cdot \cos \tilde{\omega} , \quad (59)$$

$$X_8 = X_6 \cdot \tan \beta - X_2 \cdot \sin \alpha , \quad (60)$$

$$X_9 = X_7 \cdot \tan \beta - X_3 \cdot \sin \alpha , \quad (61)$$

$$X_{10} = X_8 \cdot (R_o/p) \cdot \sin \alpha \cdot e , \quad (62)$$

$$X_{11} = \sqrt{(X_9^2 + X_{10}^2)} , \quad (63)$$

where the tabulated values of α are utilized. In the general case [$\sin(\beta) \neq 0$], obtain ξ from:

$$\xi = \tan^{-1} (X_{10}/X_9) , \quad (64)$$

and η from

$$\eta = \sin^{-1} [(R_o/p) \cdot \sin \alpha / X_{11}] . \quad (65)$$

The value of f which corresponds to the given β must be either

$$f = \xi - \eta , \quad (66)$$

or

$$f = 2\pi - (\xi + \eta) . \quad (67)$$

(The decision of which f to use requires some programming logic, governed by continuity.) Once the value of f is obtained, from the inverse of equation (21),

$$\mathcal{E} = 2 \cdot \tan^{-1} \{ \sqrt{[(1-e)/(1+e)] \cdot \tan(f/2)} \} , \quad (68)$$

with equation (20) then supply the value of time which corresponds to the chosen set of orbital elements at the isolated value of true anomaly.

Unless the orbital elements were guessed precisely, the time which has been computed will not agree with the time which was recorded as a corresponding value to each given α , β , or the (α, β) pair. What is needed is an iteration scheme which will modify the values of the orbital elements in a systematic manner until the calculated times agree with the actual times recorded at the observation site (or the times given by the driver program). Notationally, let T_{1o}, \dots, T_{5o} be the “true” times and let T_1, \dots, T_5 be the times which are calculated from equation (16). Denote U_i as

$$U_i = T_i(a, e, \tilde{\omega}, \delta\mathcal{Q}, I) - T_{io} \quad (i=0, \dots, 4), \quad (69)$$

and let an “ i ” subscript denote corresponding time-varying quantities (f , \mathcal{E} , etc.).

Suppose that the orbital elements $(a, e, \tilde{\omega}, I, \delta\mathcal{Q})$ differ from the true values of the orbital elements by amounts Δa , Δe , $\Delta\tilde{\omega}$, ΔI , and $\Delta\delta\mathcal{Q}$ (respectively). If these deviations were known precisely, one would have

$$U_i(a+\Delta a, e+\Delta e, \tilde{\omega}+\Delta\tilde{\omega}, \delta\mathcal{Q}+\Delta\delta\mathcal{Q}, I+\Delta I) = 0. \quad (70)$$

The obvious next step is to expand the U_i set via Taylor's theory to obtain a Newton iterator:

$$U_i(a+\Delta a, e+\Delta e, I+\Delta I, \tilde{\omega}+\Delta\tilde{\omega}, \delta\mathcal{L}+\Delta\delta\mathcal{L}) = U_i(a, e, I, \tilde{\omega}, \delta\mathcal{L}) + (\partial U_i/\partial a) \cdot \Delta a + (\partial U_i/\partial e) \cdot \Delta e + (\partial U_i/\partial I) \cdot \Delta I + (\partial U_i/\partial \tilde{\omega}) \cdot \Delta\tilde{\omega} + (\partial U_i/\partial \delta\mathcal{L}) \cdot \Delta\delta\mathcal{L} + \dots = 0, \quad (71)$$

where ($i = 0, \dots, 4$). In matrix notation, with y_j as any member of the ordered set of orbital elements deviations ($\Delta a, \Delta e, \Delta I, \Delta\tilde{\omega}, \Delta\delta\mathcal{L}$), and x_j any member of the ordered set of orbital elements ($a, e, I, \tilde{\omega}, \delta\mathcal{L}$), equation (71) becomes:

$$(U_i)^T = (\partial U_i/\partial x_j) \cdot (y_j)^T \quad (i = 0, \dots, 4), (j = 0, \dots, 4). \quad (72)$$

Unless $|(\partial U_i/\partial x_j)| = 0$, one can solve for

$$(y_j)^T = (\partial U_i/\partial x_j)^{-1} \cdot (U_i)^T. \quad (73)$$

The values of $a, e, I, \tilde{\omega}$, and $\delta\mathcal{L}$ can now be modified by the substitutions

$$\left. \begin{aligned} a &\rightarrow a+\Delta a \\ e &\rightarrow e+\Delta e \\ I &\rightarrow I+\Delta I \\ \tilde{\omega} &\rightarrow \tilde{\omega}+\Delta\tilde{\omega} \\ \delta\mathcal{L} &\rightarrow \delta\mathcal{L}+\Delta\delta\mathcal{L} \end{aligned} \right\} \quad (74)$$

If the new values of the orbital elements do not drive all of the U_i values to zero, the process can be continued until convergence is achieved.

One still needs to obtain the derivatives of each of the U_i with respect to each of the orbital elements, i.e., the matrix elements of $\partial U_i/\partial x_j$. Temporarily suppressing the “ i ” subscript, it is convenient to proceed through a “chain calculation” as:

$$\begin{aligned} \partial U/\partial a &= (3/2) \cdot \sqrt{(a/\mu)} \cdot (\mathcal{E} - e \cdot \sin \mathcal{E}) + \sqrt{(a^3/\mu)} (1 - e \cdot \cos \mathcal{E}) \cdot \partial \mathcal{E}/\partial a \\ &= \sqrt{(a/\mu)} \cdot [(3/2) \cdot (\mathcal{E} - e \cdot \sin \mathcal{E}) + a \cdot (1 - e \cdot \cos \mathcal{E}) \cdot \partial \mathcal{E}/\partial a], \end{aligned} \quad (75)$$

$$\partial U/\partial e = \sqrt{(a^3/\mu)} \cdot [(1 - e \cdot \cos \mathcal{E}) \cdot \partial \mathcal{E}/\partial e], \quad (76)$$

$$\partial U/\partial \tilde{\omega} = \sqrt{(a^3/\mu)} \cdot [(1 - e \cdot \cos \mathcal{E}) \cdot \partial \mathcal{E}/\partial \tilde{\omega}], \quad (77)$$

$$\partial U/\partial \Omega = \sqrt{(a^3/\mu)} \cdot [(1 - e \cdot \cos \mathcal{E}) \cdot \partial \mathcal{E}/\partial \delta\mathcal{L}], \quad (78)$$

$$\partial U/\partial I = \sqrt{(a^3/\mu)} \cdot [(1 - e \cdot \cos \mathcal{E}) \cdot \partial \mathcal{E}/\partial I]. \quad (79)$$

From equation (68):

$$\partial \mathcal{E} / \partial a = (r/a) \cdot \partial f / \partial a , \quad (80)$$

$$\partial \mathcal{E} / \partial e = [r / \sqrt{(1-e^2)}] [(\partial f / \partial e) / a - \sin f / p] , \quad (81)$$

$$\partial \mathcal{E} / \partial \tilde{\omega} = (r/a) \cdot \partial f / \partial \tilde{\omega} , \quad (82)$$

$$\partial \mathcal{E} / \partial \delta \mathcal{L} = (r/a) \cdot \partial f / \partial \delta \mathcal{L} , \quad (83)$$

$$\partial \mathcal{E} / \partial I = (r/a) \cdot \partial f / \partial I . \quad (84)$$

One will also need the derivatives of ξ from equation (64) and η from equation (65):

$$\frac{\partial \eta}{\partial a} = \frac{-[R_o \cdot \sin \alpha] \cdot (a \cdot \partial X_{11} / \partial a + X_{11})}{[a \cdot X_{11} \cdot \sqrt{(a^2 \cdot (1-e^2)^2 \cdot X_{11}^2 - [R_o \cdot \sin(\alpha)]^2)}]} , \quad (85)$$

$$\frac{\partial \eta}{\partial e} = \frac{\{[R_o \cdot \sin \alpha] / [X_{11} \cdot (1-e^2)]\} \cdot \{2 \cdot e \cdot X_{11} - (1-e^2) \cdot \partial X_{11} / \partial e\}}{\sqrt{(a^2 \cdot (1-e^2)^2 \cdot X_{11}^2 - [R_o \cdot \sin(\alpha)]^2)}} , \quad (86)$$

$$\partial \eta / \partial x = ([R_o \cdot \sin \alpha] / X_{11}) \cdot \partial X_{11} / \partial x / \sqrt{(a^2 \cdot (1-e^2)^2 \cdot X_{11}^2 - [R_o \cdot \sin \alpha]^2)} , \quad (87)$$

where $x = I, \varpi$, or $\delta \mathcal{L}$. For the derivatives of ξ , one has

$$\begin{aligned} \partial \xi / \partial x &= [X_9 \cdot (\partial X_{10} / \partial x) - X_{10} \cdot (\partial X_9 / \partial x)] / [X_9^2 + X_{10}^2] \\ &= [X_9 \cdot (\partial X_{10} / \partial x) - X_{10} \cdot (\partial X_9 / \partial x)] / X_{11}^2 , \end{aligned} \quad (88)$$

(for x any orbital element).

Using the given expression of f , equation (66), one is now in a position to calculate the derivatives of f from, say:

$$\partial f / \partial x = \partial \xi / \partial x - \partial \eta / \partial x . \quad (89)$$

The next task is to calculate the derivatives for X_0, \dots, X_{11} . These follow (with x as a generic orbital element):

$$\partial X_0 / \partial \delta \mathcal{L} = -\sin(\delta \mathcal{L} - \phi) \cdot \cos \theta , \quad (90)$$

$$\partial X_0 / \partial x = 0 , \quad (x \neq \delta \mathcal{L}) , \quad (91)$$

$$\partial X_1 / \partial I = -\sin I \cdot \sin(\delta \mathcal{L} - \phi) \cdot \cos \theta - \cos I \cdot \sin \theta , \quad (92)$$

$$\partial X_1 / \partial \delta \mathcal{L} = \cos I \cdot \cos(\delta \mathcal{L} - \phi) \cdot \cos \theta , \quad (93)$$

$$\partial X_1/\partial x = 0, \quad (x = a, e, \text{ or } \tilde{\omega}), \quad (94)$$

$$\partial X_2/\partial x = (\partial X_0/\partial x) \cdot \cos \tilde{\omega} - (\partial X_1/\partial x) \cdot \sin \tilde{\omega}, \quad (x \neq \tilde{\omega}), \quad (95)$$

$$\partial X_2/\partial \tilde{\omega} = (\partial X_0/\partial \tilde{\omega}) \cdot \cos \tilde{\omega} - (\partial X_1/\partial \tilde{\omega}) \cdot \sin \tilde{\omega} - X_0 \cdot \sin \tilde{\omega} - X_1 \cdot \cos \tilde{\omega}, \quad (96)$$

$$\partial X_3/\partial x = (\partial X_0/\partial x) \cdot \sin \tilde{\omega} - (\partial X_1/\partial x) \cdot \cos \tilde{\omega}, \quad (x \neq \tilde{\omega}), \quad (97)$$

$$\partial X_3/\partial \tilde{\omega} = (\partial X_0/\partial \tilde{\omega}) \cdot \sin \tilde{\omega} + (\partial X_1/\partial \tilde{\omega}) \cdot \cos \tilde{\omega} + X_0 \cdot \cos \tilde{\omega} - X_1 \cdot \sin \tilde{\omega}, \quad (98)$$

$$\partial X_4/\partial \delta\ell = \cos(\delta\ell - \phi), \quad (99)$$

$$\partial X_4/\partial x = 0, \quad (x \neq \delta\ell), \quad (100)$$

$$\partial X_5/\partial I = -\sin I \cdot \cos(\delta\ell - \phi), \quad (101)$$

$$\partial X_5/\partial \delta\ell = -\cos I \cdot \sin(\delta\ell - \phi), \quad (102)$$

$$\partial X_5/\partial x = 0 \quad (x \neq I, x \neq \delta\ell), \quad (103)$$

$$\partial X_6/\partial x = (\partial X_4/\partial x) \cdot \cos \tilde{\omega} + (\partial X_5/\partial x) \cdot \sin \tilde{\omega}, \quad (x \neq \tilde{\omega}), \quad (104)$$

$$\partial X_6/\partial \tilde{\omega} = (\partial X_4/\partial \tilde{\omega}) \cdot \cos \tilde{\omega} + (\partial X_5/\partial \tilde{\omega}) \cdot \sin \tilde{\omega} - X_4 \cdot \sin \tilde{\omega} + X_5 \cdot \cos \tilde{\omega}, \quad (105)$$

$$\partial X_7/\partial x = (\partial X_4/\partial x) \cdot \sin \tilde{\omega} - (\partial X_5/\partial x) \cdot \cos \tilde{\omega}, \quad (x \neq \tilde{\omega}), \quad (106)$$

$$\partial X_7/\partial \tilde{\omega} = (\partial X_4/\partial \tilde{\omega}) \cdot \sin \tilde{\omega} - (\partial X_5/\partial \tilde{\omega}) \cdot \cos \tilde{\omega} + X_4 \cdot \cos \tilde{\omega} + X_5 \cdot \sin \tilde{\omega}, \quad (107)$$

$$\partial X_8/\partial x = (\partial X_6/\partial x) \cdot \tan \beta - (\partial X_2/\partial x) \cdot \sin \alpha, \quad (108)$$

$$\partial X_9/\partial x = (\partial X_7/\partial x) \cdot \tan \beta - (\partial X_3/\partial x) \cdot \sin \alpha, \quad (109)$$

$$\partial X_{10}/\partial x = \partial X_8/\partial x, \quad (x \neq e), \quad (110)$$

$$\partial X_{10}/\partial e = \partial X_8/\partial e + R_o \cdot \sin \alpha, \quad (111)$$

$$\partial X_{11}/\partial x = [X_9 \cdot (\partial X_9/\partial x) + X_{10} \cdot (\partial X_{10}/\partial x)]/X_{11}. \quad (112)$$

If the program utilizes both the α and β table, the development is now complete. Once the orbital elements have been chosen, we can obtain the derivatives of X_0, \dots, X_{11} with respect to $(a, e, \tilde{\omega}, I, \delta\ell)$ each orbital element from equations (90) through (112). Given these derivatives, use equations (85) through (88) to obtain the derivatives of η and ξ with respect to the orbital elements, and subsequently, the derivatives of f with respect to the same variables. That allows a computation of the derivatives of ϵ (equations (80) through (84)) and finally the derivatives of U from equations (75) through (79). This yields the derivatives of a five-dimensional vector, say $(\partial U_0/\partial x)$. The process is repeated for each of the other data sets (α_i, β_i, T_i) , to construct the matrix shown in equation (72). Matrix manipulation then yields the corrections to the orbital elements from equation(s) (74).

If the information on the azimuth, α (or β), is not used, the situation is more complicated since α must be taken as another variable and equations (60), (61) and (62) must account for the fact that α is defined in terms of the assumed orbital elements. From equation (11), one can use equations (58) and (59) to write

$$\sin \alpha = r \cdot (X_6 \cdot \cos f - X_7 \cdot \sin f) / (\rho \cdot \cos \beta), \quad (113)$$

while equation (10) becomes

$$\rho = \sqrt{[r^2 + R_o^2 - 2 \cdot r \cdot R_o \cdot (X_2 \cdot \cos f - X_3 \cdot \sin f)]}. \quad (114)$$

Equations (107) through (111) would be modified to read:

$$\partial X_8 / \partial x = (\partial X_6 / \partial x) \cdot \tan \beta - (\partial X_2 / \partial x) \cdot \sin \alpha - X_2 \cdot \cos \alpha \cdot \partial \alpha / \partial x, \quad (115)$$

$$\partial X_9 / \partial x = (\partial X_7 / \partial x) \cdot \tan \beta - (\partial X_3 / \partial x) \cdot \sin \alpha - X_3 \cdot \cos \alpha \cdot \partial \alpha / \partial x, \quad (116)$$

$$\partial X_{10} / \partial x = \partial X_8 / \partial x + R_o / p \cdot \cos \alpha \cdot \partial \alpha / \partial x \quad (x \neq e), \quad (117)$$

$$\partial X_{10} / \partial e = \partial X_8 / \partial e + R_o \cdot \sin \alpha + (R_o / p) \cdot \cos \alpha \cdot \partial \alpha / \partial x \quad (x = e). \quad (118)$$

From equation (114) comes

$$\begin{aligned} \partial \rho / \partial x = \{ & (r - R_o) \cdot \partial r / \partial x - r \cdot R_o \cdot [\cos f \cdot (\partial X_2 / \partial x - X_3 \cdot \partial f / \partial x) \\ & - \sin f \cdot (\partial X_3 / \partial x + X_2 \cdot \partial f / \partial x)] \} / \rho, \end{aligned} \quad (119)$$

which is needed to evaluate $\partial \alpha / \partial x$; from equation (113) one obtains both

$$\begin{aligned} \cos \alpha \cdot \partial \alpha / \partial x = \{ & \partial r / \partial x \cdot (X_6 \cdot \cos f - X_7 \cdot \sin f) + r \cdot [(\partial X_6 / \partial x - X_7 \cdot \partial f / \partial x) \cdot \cos f \\ & - (X_6 \cdot \partial f / \partial x + \partial X_7 / \partial x) \cdot \sin f] \} / (\rho \cdot \cos \beta) - r \cdot (X_6 \cdot \cos f - X_7 \cdot \sin f) \cdot \partial \rho / \partial x / (\rho^2 \cdot \cos \beta), \end{aligned} \quad (120)$$

and

$$\cos \alpha = \sqrt{[\rho^2 \cdot \cos^2 \beta - r^2 \cdot (X_6 \cdot \cos f - X_7 \cdot \sin f)^2]} / (\rho \cdot \cos \beta). \quad (121)$$

In order to take the derivatives of α with respect to each orbital element, one would also need the derivatives of r with respect to the same variables. Using equation (19), one finds

$$\partial r / \partial a = 1 - e \cdot \cos \mathcal{E} + a \cdot e \cdot \sin \mathcal{E} \cdot \partial \mathcal{E} / \partial a, \quad (122)$$

$$\partial r / \partial e = a \cdot \cos \mathcal{E} + a \cdot e \cdot \sin \mathcal{E} \cdot \partial \mathcal{E} / \partial e. \quad (123)$$

Using equations (115) through (123) allows the measured values for α to be ignored, but ignoring the measured values is paid for with the need for increased computation. Similar comments are applicable to the case where tabular values of α are assumed to be known but β is treated as a computable quantity. In the numerical results that are presented in the next section, tabular values of both α and β were assumed to be known.

NUMERICAL RESULTS

The above theory was programmed in COMMON LISP on a Symbolics 6370. That platform allows for rapid prototyping and ease of equation development. The entire set of equations performed quite well; the Newton iteration scheme can converge a correct set of orbital elements from rather bad guesses.

There has been an implicit assumption that there is a unique set of orbital elements which will produce the given table of observations. Although no attempt was made to establish uniqueness, one case was inadvertently found where the solution was not mathematically unique, but the extraneous solution did not correspond to a physically realistic orbit. Specifically, for the inputs of α , β , and time from a two-dimensional suborbital case (with true $a = 6,018.739$, $e = 0.724$, $\tilde{\omega} = 225$, $I = 0$, and $\delta\Omega = 0$), started from a rather precise initial set of guesses that assumed $a = 6,020$, $e = 0.5$, $\tilde{\omega} = 350$, $I = 0$, $\delta\Omega = 0$. The convergence criteria was met with $a = 9,666.27930$, $e = -0.17980$, $\tilde{\omega} = -25.54499$, $I = 0$, and $\delta\Omega = 0$. This is not a physically realistic orbit ($e < 0$, $a > 0$), however, and is easily eliminated by requiring that $e \geq 0$. Additional constraints should be added to the iteration scheme, i.e., require that $a \cdot (1+e) \geq R_o$, $-\pi/2 \leq I \leq \pi/2$, and $0 \leq \delta\Omega \leq \pi$. In the case of tracking a comet or an asteroid (which are usually elliptical with respect to the Sun but hyperbolic with respect to the Earth), alternative constraints obviously would have to be used.

In regard to two-dimensional iterations, in general, note that the convergence scheme is valid for those cases provided that the reduced dimension of the iteration space is accounted for. A three-dimensional iteration, faced with a two-dimensional problem, will encounter a singular matrix unless precautions are taken. Furthermore, when a two-dimensional problem is undertaken, one must take $\alpha = 3\pi/2$ due to the choice of the coordinate system.

During the computation procedure, the equation for η , equation (31), was particularly treacherous in that it is rather easy for $(R_o/p) \cdot \sin \alpha/X11$ to underflow or overflow from the range $-1 \leq \sin^{-1} \leq 1$ and produce complex values for α . The LISP language easily handled the complex values, but it balked at attempting to double-float the results. This was handled by the crude, though effective, artifice of simply setting α to either $3\pi/2$ or $\pi/2$ depending upon the direction in which the insult occurred. As the iteration scheme approached more accurate values of the orbital elements, the problem disappeared. Iteration to isolate a satellite orbit tends to monotone convergence, but isolation of very short range missiles (~200 km) becomes extremely difficult since the trajectories have eccentricities that approach unity. For those cases, the Newton iteration, as presented here, is virtually inapplicable.

Another difficulty, often present in Newtonian iteration schemes, was that the corrections for Δa , Δe , $\Delta \tilde{\omega}$, ΔI and $\Delta \delta\Omega$ were often so large that the iteration scheme began to wander aimlessly. Two methods were used to circumvent this problem. One option measured the magnitude of the errors and adjusted a "creep factor" according to the size of the errors. Another scheme placed absolute bounds on the allowable changes that could be made by any variable in a given iteration. This report was written to demonstrate a new approach to the angles-only problem, so no attempt was made to develop an optimal iteration scheme. Since the angles-only problem is important in the real world, it is expected that specific iteration schemes to optimize convergence may be forthcoming in the future.

Two illustrative examples are given here to demonstrate the use of the equations given earlier. As mentioned previously, the first of these is a rather standard satellite orbit which is numerically described in Table 1; the fact that 16 sets of data are recorded is purely arbitrary. A subset of the data displayed in Table 1 is shown in Table 2. This is the entire set of data sent to the iteration scheme. As explained, the numerical examples used the values of α and β along the time of the observations, so that neither α nor

β were calculated from the other as a part of the study. The iteration scheme converged the proper elements from the input guesses in 26 iterations (Table 3). Note that the figure of merit for the convergence (last column, Table 3) is monotone decreasing. The error calculation is defined as $\sqrt{U_0^2+U_1^2+U_2^2+U_3^2+U_4^2}$.

Table 4 demonstrates the same data as Table 1, but this time for a suborbital vehicle. The case was deliberately taken as equatorial so that a two-dimensional iteration could be demonstrated. Since only three orbital elements ($a, e, \tilde{\omega}$) need to be isolated, one can make-do with only three readings. For a two-dimensional case, if the tracking station is located in the plane of the orbit, the azimuth angle, α , is meaningless. Thus, only three readings are needed. Again, the end points were $\beta = 0$ or $\beta = \pi$ were included, but this is arbitrary. Table 4 shows the results of the iteration scheme from very poor initial guesses; indeed, the guesses are about as bad as they can meaningfully be. The iteration scheme does not display monotone convergence and appears to wander aimless for 61 of the 107 iterations that were needed to converge the case.

An attempt was made to further stress the iteration scheme by requesting an isolation of the 200-km range suborbital planar case, but convergence was never attained. Certainly, the minimal Newton iteration presented here can be strengthened by any of several known methods.

CONCLUSIONS

The preceding theory has derived another solution to the “angles-only” problem. This method, possibly used in conjunction with the alternative methods covered in reference 1, has the potential to decrease the amount of hardware that is currently required for rendezvous and missile tracking.

The numerical work that is presented demonstrates that the theory yields a practical scheme that actually solves the problem. Unfortunately, it also indicates that additional research is required to extend numerical convergence to eccentricities which are very close to unity.

A planned future paper will relax the requirement of an Earth-fixed observer and treat the case of an observer in an orbiting satellite.

Table 1. First example.

SEMI-MAJOR AXIS (A)=7420. KM, ECC=.10000 INC(I)=95.000 DEG., ARG. PERIGEE(ω)=25.000 DEG., LONG. ASC. NODE(Ω)=33.000 DEG.
APPARITION OCCURS AT $f=8.481$ deg. [$T=122.154$ sec.] AND OCCULTATION OCCURS AT $f=50.309$ deg. [$T=740.883$ sec.]

TRUE ANOMOLY, DEG.	RADIUS, KM.	RANGE, KM.	ECC. ANOMOLY, DEG.	TIME, SEC.
0 $f=8.48133608$	$r=6684.64603564$	$P=2001.40179057$	$E=7.67420293$	$T=122.15382475$
1 $f=11.33937028$	$r=6689.87187027$	$P=1702.55541086$	$E=10.26292799$	$T=163.40242366$
2 $f=14.19230929$	$r=6696.58128091$	$P=1406.84597518$	$E=12.84934444$	$T=204.65102256$
3 $f=17.03891388$	$r=6704.75468903$	$P=1117.35905908$	$E=15.43288791$	$T=245.89962147$
4 $f=19.87797554$	$r=6714.36839048$	$P=841.02426446$	$E=18.01300611$	$T=287.14822037$
5 $f=22.70832198$	$r=6725.39470844$	$P=596.64903616$	$E=20.58916104$	$T=328.89681928$
6 $f=25.52882210$	$r=6737.80216907$	$P=440.75876006$	$E=23.16083097$	$T=369.64541818$
7 $f=28.38039058$	$r=6751.55569755$	$P=470.56098382$	$E=25.72751237$	$T=410.89401708$
8 $f=31.13599196$	$r=6766.61683174$	$P=660.49270407$	$E=28.28872158$	$T=452.14261599$
9 $f=33.92064421$	$r=6782.94395090$	$P=914.90251289$	$E=30.84399635$	$T=493.39121489$
10 $f=36.69142178$	$r=6800.49251644$	$P=1192.33738686$	$E=33.39289717$	$T=534.63981308$
11 $f=39.44745811$	$r=6819.21532193$	$P=1479.03113160$	$E=35.93500846$	$T=575.88841270$
12 $f=42.18794762$	$r=6839.06274951$	$P=1769.64478692$	$E=38.46993949$	$T=617.13701161$
13 $f=44.91214716$	$r=6859.98302993$	$P=2061.70019529$	$E=40.99732514$	$T=658.38561051$
14 $f=47.61937693$	$r=6881.92250357$	$P=2353.86307735$	$E=43.51682652$	$T=699.63420942$
15 $f=50.30902095$	$r=6904.82588003$	$P=2645.32323647$	$E=46.02813134$	$T=740.88200832$

AZIMUTH, DEG.	ELEVATION, DEG.	LONGITUDE, DEG.	LATITUDE, DEG.	LONGITUDE (RADAR) DEG.
0 $\alpha=-58.15003437$	$\beta=-.00000113$	$\Phi=61.44889048$	$\Theta=18.44669380$	$\Phi_s=77.00000000$
1 $\alpha=-57.00645798$	$\beta=3.10616670$	$\Phi=64.07291615$	$\Theta=19.86970746$	$\Phi_s=77.17186916$
2 $\alpha=-55.34118427$	$\beta=6.99699965$	$\Phi=66.73900244$	$\Theta=21.25119328$	$\Phi_s=77.34373832$
3 $\alpha=-52.71266671$	$\beta=12.25898824$	$\Phi=69.44867889$	$\Theta=22.58706924$	$\Phi_s=77.51560749$
4 $\alpha=-48.00953651$	$\beta=20.15520607$	$\Phi=72.20310392$	$\Theta=23.87327468$	$\Phi_s=77.68747665$
5 $\alpha=-37.56514360$	$\beta=33.45800818$	$\Phi=75.00300642$	$\Theta=25.10579627$	$\Phi_s=77.85934581$
6 $\alpha=-4.22028134$	$\beta=53.59066411$	$\Phi=77.84862649$	$\Theta=26.28069784$	$\Phi_s=77.803121497$
7 $\alpha=64.33158348$	$\beta=128.72017840$	$\Phi=80.73965749$	$\Theta=27.39415375$	$\Phi_s=78.20308413$
8 $\alpha=98.55732702$	$\beta=146.32232990$	$\Phi=83.67519231$	$\Theta=28.44248594$	$\Phi_s=78.37495338$
9 $\alpha=99.36079597$	$\beta=157.36021261$	$\Phi=86.65367667$	$\Theta=29.42220398$	$\Phi_s=78.54682246$
10 $\alpha=103.52061532$	$\beta=164.18076975$	$\Phi=89.67287325$	$\Theta=30.33004762$	$\Phi_s=78.71869162$
11 $\alpha=105.90245379$	$\beta=168.89052738$	$\Phi=92.72983999$	$\Theta=31.16303074$	$\Phi_s=78.89056078$
12 $\alpha=107.42823026$	$\beta=172.45952834$	$\Phi=95.82092612$	$\Theta=31.91848556$	$\Phi_s=79.06242995$
13 $\alpha=108.47830717$	$\beta=175.35471125$	$\Phi=98.94178883$	$\Theta=32.59410553$	$\Phi_s=79.23429911$
14 $\alpha=109.23705338$	$\beta=177.82162762$	$\Phi=102.00743269$	$\Theta=33.18798516$	$\Phi_s=79.40616827$
15 $\alpha=109.80439856$	$\beta=179.99999761$	$\Phi=105.25227275$	$\Theta=33.69865517$	$\Phi_s=79.57803743$

Table 2. Representative data of entire package sent to iterator.

(H, Φ , Φ_s , Θ , R ASSUMED KNOWN)			
$T=122.15382475$	0 $\alpha=-58.15003437$	$\beta=-.00000113$	
$T=276.83607064$	1 $\alpha=-49.49765192$	$\beta=17.81825854$	
$T=431.51831654$	2 $\alpha=81.48848503$	$\beta=41.79462703$	
$T=586.20856243$	3 $\alpha=186.34412297$	$\beta=169.86594977$	
$T=740.88200832$	4 $\alpha=109.80439856$	$\beta=179.99999761$	

Table 3. Results of iteration scheme.

ORIGINAL GUESSES: A=7000.00000 km Ecc=.00000 I=27.00000 deg ω =.00000 deg Ω =.00000 deg

ITERATION #0	A=6997.11928 km	Ecc=.00153	$\omega=80.70312$ deg	I=27.63809 deg	$\Omega=359.66414$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=2009.63630547$
ITERATION #1	A=6976.37418 km	Ecc=.01593	$\omega=84.53330$ deg	I=34.23148 deg	$\Omega=000.10470$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=1989.44887953$
ITERATION #2	A=6984.14600 km	Ecc=.02570	$\omega=84.30058$ deg	I=34.72697 deg	$\Omega=005.38340$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=1784.30766470$
ITERATION #3	A=7001.23236 km	Ecc=.03438	$\omega=85.26028$ deg	I=35.26693 deg	$\Omega=009.02111$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=1605.87646740$
ITERATION #4	A=7023.14477 km	Ecc=.04188	$\omega=86.72678$ deg	I=35.64320 deg	$\Omega=011.73783$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=1445.02945689$
ITERATION #5	A=7047.51661 km	Ecc=.04841	$\omega=88.35303$ deg	I=35.86671 deg	$\Omega=013.91800$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=1300.14138118$
ITERATION #6	A=7072.80632 km	Ecc=.05411	$\omega=89.97658$ deg	I=35.97578 deg	$\Omega=015.75416$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=1169.70535455$
ITERATION #7	A=7098.31449 km	Ecc=.05910	$\omega=11.51927$ deg	I=36.00527 deg	$\Omega=017.35192$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=1052.31412419$
ITERATION #8	A=7160.51885 km	Ecc=.07010	$\omega=15.08418$ deg	I=35.94827 deg	$\Omega=020.90512$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0946.67896590$
ITERATION #9	A=7212.08151 km	Ecc=.07731	$\omega=17.84513$ deg	I=35.62406 deg	$\Omega=023.55637$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0708.35808592$
ITERATION #10	A=7254.11223 km	Ecc=.08240	$\omega=19.81318$ deg	I=35.33142 deg	$\Omega=025.69427$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0530.02498390$
ITERATION #11	A=7288.44022 km	Ecc=.08623	$\omega=21.20240$ deg	I=35.13819 deg	$\Omega=027.41042$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0396.60902847$
ITERATION #12	A=7316.43888 km	Ecc=.08921	$\omega=22.19628$ deg	I=35.02999 deg	$\Omega=028.75806$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0296.80609278$
ITERATION #13	A=7339.12253 km	Ecc=.09158	$\omega=22.91851$ deg	I=34.97731 deg	$\Omega=029.79734$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0222.14316318$
ITERATION #14	A=7357.31780 km	Ecc=.09347	$\omega=23.44940$ deg	I=34.95647 deg	$\Omega=030.58963$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0166.27911558$
ITERATION #15	A=7371.75187 km	Ecc=.09497	$\omega=23.84247$ deg	I=34.95223 deg	$\Omega=031.18950$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0124.47395496$
ITERATION #16	A=7394.40775 km	Ecc=.09732	$\omega=24.42709$ deg	I=34.95924 deg	$\Omega=032.09412$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0093.18528045$
ITERATION #17	A=7406.78486 km	Ecc=.09861	$\omega=24.71504$ deg	I=34.97549 deg	$\Omega=032.54899$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0046.30360731$
ITERATION #18	A=7413.29293 km	Ecc=.09929	$\omega=24.85799$ deg	I=34.98695 deg	$\Omega=032.77596$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0023.02310822$
ITERATION #19	A=7416.62822 km	Ecc=.09964	$\omega=24.92917$ deg	I=34.99342 deg	$\Omega=032.88883$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0011.45162358$
ITERATION #20	A=7418.31322 km	Ecc=.09982	$\omega=24.96465$ deg	I=34.99676 deg	$\Omega=032.94487$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0005.69708321$
ITERATION #21	A=7419.15825 km	Ecc=.09991	$\omega=24.98236$ deg	I=34.99843 deg	$\Omega=032.97267$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0002.83453385$
ITERATION #22	A=7419.58049 km	Ecc=.09995	$\omega=24.99119$ deg	I=34.99924 deg	$\Omega=032.98645$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0001.41037319$
ITERATION #23	A=7420.00172 km	Ecc=.10000	$\omega=25.00001$ deg	I=35.00003 deg	$\Omega=033.00012$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0000.70177748$
ITERATION #24	A=7420.00025 km	Ecc=.10000	$\omega=25.00000$ deg	I=35.00000 deg	$\Omega=033.00000$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0000.00353102$
ITERATION #25	A=7420.00026 km	Ecc=.10000	$\omega=25.00000$ deg	I=35.00000 deg	$\Omega=033.00000$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0000.00001940$
ITERATION #26	A=7420.00026 km	Ecc=.10000	$\omega=25.00000$ deg	I=35.00000 deg	$\Omega=033.00000$ deg	$\sqrt{[\text{SUM (ERRORS)}^2]}=0000.00000010$

CONVERGED SOLUTION: A=7420.00026 km Ecc=.10000 I=35.00000 deg ω =25.00000 deg Ω =33.00000 deg
 $\sqrt{[\text{SUM (ERRORS)}^2]}=.00000010$

Table 4. Second example.

SEMI-MAJOR AXIS (A)=6019. KM, ECC=.72428 INC(I)=.000 DEG., ARG. PERIGEE(ω)=225.000 DEG., LONG. ASC. NODE(Ω)=.000 DEG.
 APPARITION OCCURS AT f=154.991 deg. [T=1120.749 sec.] AND OCCULTATION OCCURS AT f=219.128 deg. [T=3932.605 sec.]

TRUE ANOMOLY, DEG.	RADIUS, KM.	RANGE, KM.	ECC. ANOMOLY, DEG.	TIME, SEC.
0 f=154.99056464	r=8327.03917718	p=5353.56799812	ϵ =121.97277140	T=1120.74879014
1 f=159.84812332	r=8940.30401130	p=5316.69080146	ϵ =132.08228159	T=1308.20587948
2 f=164.13710554	r=9434.24059567	p=5301.21356239	ϵ =141.50250033	T=1495.66296882
3 f=168.04340171	r=9810.44038207	p=5278.16143365	ϵ =150.64963478	T=1683.12005817
4 f=171.69290062	r=10099.63085244	p=5226.61914198	ϵ =159.41388293	T=1870.57714751
5 f=175.17006710	r=10282.40302165	p=5131.41085411	ϵ =167.97870649	T=2058.03423685
6 f=178.57269911	r=10369.54893382	p=4981.20243176	ϵ =176.43164170	T=2245.49132620
7 f=181.94118337	r=10362.37915844	p=4767.10213407	ϵ =184.85198369	T=2432.94841554
8 f=185.34530128	r=10260.78748541	p=4481.69994810	ϵ =193.31671190	T=2620.40550488
9 f=188.85039710	r=10063.25051039	p=4118.50129078	ϵ =201.90596867	T=2807.86259422
10 f=192.53242203	r=9766.70455542	p=3671.85978114	ϵ =210.70915095	T=2995.31968357
11 f=196.40778574	r=9366.20463255	p=3137.99737918	ϵ =219.83291254	T=3182.77677291
12 f=200.04937183	r=8854.87299320	p=2519.60614320	ϵ =229.41310022	T=3370.23386225
13 f=205.81589808	r=8222.35062730	p=1846.25538555	ϵ =239.63526416	T=3557.69095160
14 f=211.71203239	r=7454.43313420	p=1281.26945377	ϵ =250.77108362	T=3745.14804094
15 f=219.12843774	r=6530.64834910	p=1403.73789664	ϵ =263.25619535	T=3932.60513028

AZIMUTH, DEG.	ELEVATION, DEG.	LONGITUDE, DEG.	LATITUDE, DEG.	LONGITUDE (RADAR) DEG.
0 α =-90.00000000	β =-.00000000	ϕ =19.99056464	Θ =-.00000000	Φ =60.00000000
1 α =-90.00000000	β =9.31971328	ϕ =24.04812332	Θ =-.00000000	Φ =60.78107121
2 α =-90.00000000	β =17.40117751	ϕ =29.13710554	Θ =-.00000000	Φ =61.56214241
3 α =-90.00000000	β =24.44702159	ϕ =33.04340171	Θ =-.00000000	Φ =62.34321362
4 α =-90.00000000	β =30.66801405	ϕ =36.69290062	Θ =-.00000000	Φ =63.12428482
5 α =-90.00000000	β =36.26370108	ϕ =40.17806710	Θ =-.00000000	Φ =63.90535603
6 α =-90.00000000	β =41.1969757	ϕ =43.57269911	Θ =-.00000000	Φ =64.68642723
7 α =-90.00000000	β =46.31600507	ϕ =46.94118337	Θ =-.00000000	Φ =65.46749844
8 α =-90.00000000	β =51.14502534	ϕ =50.34530128	Θ =-.00000000	Φ =66.24856964
9 α =-90.00000000	β =56.14476239	ϕ =53.85039710	Θ =-.00000000	Φ =67.02964085
10 α =-90.00000000	β =61.66664772	ϕ =57.53242289	Θ =-.00000000	Φ =67.81071206
11 α =-90.00000000	β =68.33790782	ϕ =61.40770574	Θ =-.00000000	Φ =68.59170326
12 α =-90.00000000	β =77.52662540	ϕ =65.84937183	Θ =-.00000000	Φ =69.37285447
13 α =-90.00000000	β =87.05064752	ϕ =70.81589808	Θ =-.00000000	Φ =70.15392567
14 α =-90.00000000	β =125.04723511	ϕ =76.71203239	Θ =-.00000000	Φ =70.93499608
15 α =-90.00000000	β =179.99998791	ϕ =84.12843774	Θ =-.00000000	Φ =71.71606808

Table 5. Representative data of entire package sent to iterator.

(H, ϕ , δ , Θ , R ASSUMED KNOWN)			
T=1120.74879014	β =-.00000000		
T=2526.67696021	β =48.72566711		
T=3932.60513028	β =179.99998791		

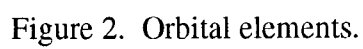
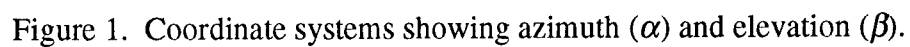
Table 6. Results of iteration scheme.

ORIGINAL GUESSES: A=6378.00000 km Ecc=.00000 ω =-.00000 deg Ω =-.00000 deg	
ITERATION #0: A=6377.82547 km Ecc=.01000 ω =246.53286 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3342.25372390	
ITERATION #1: A=6377.65093 km Ecc=.11000 ω =275.73814 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =1707.90104467	
ITERATION #2: A=6377.47640 km Ecc=.21000 ω =243.58550 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =1563.56658065	
ITERATION #3: A=6377.30187 km Ecc=.31000 ω =214.12491 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =0967.94274041	
ITERATION #4: A=6377.47640 km Ecc=.41000 ω =258.37404 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =1210.41028906	
ITERATION #5: A=6377.30187 km Ecc=.51000 ω =119.31538 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =0862.33919423	
ITERATION #6: A=6377.47640 km Ecc=.41000 ω =161.91792 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =4237.05560753	
ITERATION #7: A=6377.30187 km Ecc=.31000 ω =143.56112 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3587.49167198	
ITERATION #8: A=6377.47640 km Ecc=.21000 ω =002.73302 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3902.12313582	
ITERATION #9: A=6377.65093 km Ecc=.11000 ω =102.47098 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3642.75359697	
ITERATION #10: A=6377.82547 km Ecc=.01000 ω =218.38686 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3958.24350289	
ITERATION #11: A=6377.65093 km Ecc=.11000 ω =076.02424 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =1850.50353792	
ITERATION #12: A=6377.82547 km Ecc=.01000 ω =060.90440 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =4175.96923678	
ITERATION #13: A=6377.65093 km Ecc=.11000 ω =110.29098 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =5569.74171210	
ITERATION #14: A=6377.82547 km Ecc=.01000 ω =133.66279 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3903.96075415	
ITERATION #15: A=6378.00000 km Ecc=.01000 ω =118.56111 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3621.66578190	
ITERATION #16: A=6378.00000 km Ecc=.01000 ω =228.70121 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3759.25058461	
ITERATION #17: A=6377.82547 km Ecc=.11000 ω =336.81249 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =1828.42076609	
ITERATION #18: A=6378.00000 km Ecc=.01000 ω =056.21260 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3104.59657251	
ITERATION #19: A=6377.82547 km Ecc=.11000 ω =036.52690 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =4543.88574404	
ITERATION #20: A=6378.00000 km Ecc=.01000 ω =107.39903 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =4167.53932133	
ITERATION #21: A=6378.00000 km Ecc=.01000 ω =230.21842 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3783.94734648	
ITERATION #22: A=6377.82547 km Ecc=.11000 ω =097.93358 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =1756.34696722	
ITERATION #23: A=6378.00000 km Ecc=.01000 ω =262.73277 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3991.99014902	
ITERATION #24: A=6378.00000 km Ecc=.01000 ω =037.54403 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =1758.09479345	
ITERATION #25: A=6378.00000 km Ecc=.01000 ω =074.54306 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =4138.43426753	
ITERATION #26: A=6378.00000 km Ecc=.01000 ω =274.77163 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =4115.06597338	
ITERATION #27: A=6378.00000 km Ecc=.01000 ω =047.80174 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =1855.01818369	
ITERATION #28: A=6378.00000 km Ecc=.01000 ω =322.64812 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =4360.17724804	
ITERATION #29: A=6378.00000 km Ecc=.01000 ω =062.38489 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =2705.93322260	
ITERATION #30: A=6377.82547 km Ecc=.11000 ω =116.39484 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =5573.56804375	
ITERATION #31: A=6378.00000 km Ecc=.01000 ω =059.07265 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3864.88321210	
ITERATION #32: A=6377.82547 km Ecc=.11000 ω =354.23826 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =4606.71200293	
ITERATION #33: A=6378.00000 km Ecc=.01000 ω =326.15469 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3371.70846483	
ITERATION #34: A=6378.00000 km Ecc=.01000 ω =028.42436 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =2762.87190362	
ITERATION #35: A=6378.00000 km Ecc=.01000 ω =252.93308 deg $\sqrt{[\text{SUM (ERRORS)}^2]}$ =3943.68348011	

Table 6. Results of iteration scheme (continued).

ITERATION	#36:	A=6378.00000	kn	Ecc=.01000	ω =064.59755	deg	✓[SUM (ERRORS) ²]=1715.94468123
ITERATION	#37:	A=6377.82547	kn	Ecc=.11000	ω =125.01488	deg	✓[SUM (ERRORS) ²]=5579.52089429
ITERATION	#38:	A=6378.00000	kn	Ecc=.01000	ω =295.14937	deg	✓[SUM (ERRORS) ²]=3814.22587824
ITERATION	#39:	A=6378.00000	kn	Ecc=.01000	ω =059.07106	deg	✓[SUM (ERRORS) ²]=2112.08775784
ITERATION	#40:	A=6377.82547	kn	Ecc=.11000	ω =354.26307	deg	✓[SUM (ERRORS) ²]=4606.67699080
ITERATION	#41:	A=6378.00000	kn	Ecc=.01000	ω =325.54414	deg	✓[SUM (ERRORS) ²]=3372.17423267
ITERATION	#42:	A=6378.00000	kn	Ecc=.01000	ω =034.50583	deg	✓[SUM (ERRORS) ²]=2752.92595544
ITERATION	#43:	A=6378.00000	kn	Ecc=.01000	ω =132.14604	deg	✓[SUM (ERRORS) ²]=4073.28820556
ITERATION	#44:	A=6378.00000	kn	Ecc=.01000	ω =121.06298	deg	✓[SUM (ERRORS) ²]=3628.40253180
ITERATION	#45:	A=6378.00000	kn	Ecc=.01000	ω =181.18194	deg	✓[SUM (ERRORS) ²]=3687.17028436
ITERATION	#46:	A=6377.82547	kn	Ecc=.11000	ω =094.81280	deg	✓[SUM (ERRORS) ²]=3172.60797744
ITERATION	#47:	A=6378.00000	kn	Ecc=.01000	ω =291.13616	deg	✓[SUM (ERRORS) ²]=4015.96918752
ITERATION	#48:	A=6378.00000	kn	Ecc=.01000	ω =146.17872	deg	✓[SUM (ERRORS) ²]=2053.68258407
ITERATION	#49:	A=6378.00000	kn	Ecc=.01000	ω =343.47329	deg	✓[SUM (ERRORS) ²]=3580.81284395
ITERATION	#50:	A=6378.00000	kn	Ecc=.01000	ω =218.86757	deg	✓[SUM (ERRORS) ²]=3030.67410247
ITERATION	#51:	A=6377.82547	kn	Ecc=.11000	ω =055.29646	deg	✓[SUM (ERRORS) ²]=1845.65847847
ITERATION	#52:	A=6378.00000	kn	Ecc=.21000	ω =048.84146	deg	✓[SUM (ERRORS) ²]=4523.58950091
ITERATION	#53:	A=6377.82547	kn	Ecc=.31000	ω =268.19530	deg	✓[SUM (ERRORS) ²]=4415.62354477
ITERATION	#54:	A=6377.65093	kn	Ecc=.41000	ω =038.99094	deg	✓[SUM (ERRORS) ²]=0964.67445113
ITERATION	#55:	A=6377.47640	kn	Ecc=.31000	ω =211.81071	deg	✓[SUM (ERRORS) ²]=4293.98179749
ITERATION	#56:	A=6377.65093	kn	Ecc=.41000	ω =263.74250	deg	✓[SUM (ERRORS) ²]=1283.33023873
ITERATION	#57:	A=6377.47640	kn	Ecc=.51000	ω =083.08813	deg	✓[SUM (ERRORS) ²]=1011.94406805
ITERATION	#58:	A=6377.30187	kn	Ecc=.61000	ω =312.47459	deg	✓[SUM (ERRORS) ²]=4456.22739218
ITERATION	#59:	A=6377.12734	kn	Ecc=.71000	ω =138.56418	deg	✓[SUM (ERRORS) ²]=2377.60300719
ITERATION	#60:	A=6377.30187	kn	Ecc=.81000	ω =213.83595	deg	✓[SUM (ERRORS) ²]=3887.10052500
ITERATION	#61:	A=6377.47640	kn	Ecc=.75529	ω =225.56000	deg	✓[SUM (ERRORS) ²]=1250.86099995
ITERATION	#62:	A=6277.47640	kn	Ecc=.71739	ω =224.33091	deg	✓[SUM (ERRORS) ²]=0460.12395739
ITERATION	#63:	A=6177.47640	kn	Ecc=.71899	ω =224.13317	deg	✓[SUM (ERRORS) ²]=0330.20472467
ITERATION	#64:	A=6077.47640	kn	Ecc=.72094	ω =224.66098	deg	✓[SUM (ERRORS) ²]=0217.45002740
ITERATION	#65:	A=6002.18338	kn	Ecc=.72299	ω =224.86027	deg	✓[SUM (ERRORS) ²]=0088.15408107
ITERATION	#66:	A=6022.73748	kn	Ecc=.72463	ω =225.13766	deg	✓[SUM (ERRORS) ²]=0020.36231904
ITERATION	#67:	A=6016.76933	kn	Ecc=.72419	ω =224.98929	deg	✓[SUM (ERRORS) ²]=0008.57612011
ITERATION	#68:	A=6020.10635	kn	Ecc=.72433	ω =225.05943	deg	✓[SUM (ERRORS) ²]=0005.34985398
ITERATION	#69:	A=6017.00717	kn	Ecc=.72425	ω =224.96852	deg	✓[SUM (ERRORS) ²]=0003.48845386
ITERATION	#70:	A=6019.36574	kn	Ecc=.72430	ω =225.02634	deg	✓[SUM (ERRORS) ²]=0002.32481090
ITERATION	#71:	A=6018.32287	kn	Ecc=.72427	ω =224.98242	deg	✓[SUM (ERRORS) ²]=0001.55106925
ITERATION	#72:	A=6019.01815	kn	Ecc=.72429	ω =225.01173	deg	✓[SUM (ERRORS) ²]=0001.03537443
ITERATION	#73:	A=6018.55427	kn	Ecc=.72427	ω =224.99218	deg	✓[SUM (ERRORS) ²]=0000.69857852
ITERATION	#74:	A=6018.86368	kn	Ecc=.72429	ω =225.00522	deg	✓[SUM (ERRORS) ²]=0000.46077383
ITERATION	#75:	A=6018.65724	kn	Ecc=.72428	ω =224.99652	deg	✓[SUM (ERRORS) ²]=0000.30736057
ITERATION	#76:	A=6018.79495	kn	Ecc=.72428	ω =225.00232	deg	✓[SUM (ERRORS) ²]=0000.20506258
ITERATION	#77:	A=6018.70308	kn	Ecc=.72428	ω =224.99845	deg	✓[SUM (ERRORS) ²]=0000.13679601
ITERATION	#78:	A=6018.76437	kn	Ecc=.72428	ω =225.00103	deg	✓[SUM (ERRORS) ²]=0000.09126299
ITERATION	#79:	A=6018.72348	kn	Ecc=.72428	ω =224.99931	deg	✓[SUM (ERRORS) ²]=0000.06088258
ITERATION	#80:	A=6018.75075	kn	Ecc=.72428	ω =225.00046	deg	✓[SUM (ERRORS) ²]=0000.04061689
ITERATION	#81:	A=6018.73256	kn	Ecc=.72428	ω =224.99969	deg	✓[SUM (ERRORS) ²]=0000.02709631
ITERATION	#82:	A=6018.74470	kn	Ecc=.72428	ω =225.00021	deg	✓[SUM (ERRORS) ²]=0000.01807675
ITERATION	#83:	A=6018.73660	kn	Ecc=.72428	ω =224.99986	deg	✓[SUM (ERRORS) ²]=0000.01205941
ITERATION	#84:	A=6018.74208	kn	Ecc=.72428	ω =225.00009	deg	✓[SUM (ERRORS) ²]=0000.00804516
ITERATION	#85:	A=6018.73840	kn	Ecc=.72428	ω =224.99994	deg	✓[SUM (ERRORS) ²]=0000.00536712
ITERATION	#86:	A=6018.74088	kn	Ecc=.72428	ω =225.00004	deg	✓[SUM (ERRORS) ²]=0000.00358055
ITERATION	#87:	A=6018.73920	kn	Ecc=.72428	ω =224.99997	deg	✓[SUM (ERRORS) ²]=0000.00238867
ITERATION	#88:	A=6018.74027	kn	Ecc=.72428	ω =225.00002	deg	✓[SUM (ERRORS) ²]=0000.00159355
ITERATION	#89:	A=6018.73955	kn	Ecc=.72428	ω =224.99999	deg	✓[SUM (ERRORS) ²]=0000.00106309
ITERATION	#90:	A=6018.74003	kn	Ecc=.72428	ω =225.00001	deg	✓[SUM (ERRORS) ²]=0000.00070922
ITERATION	#91:	A=6018.73971	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00047314
ITERATION	#92:	A=6018.73992	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00031564
ITERATION	#93:	A=6018.73978	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00021057
ITERATION	#94:	A=6018.73988	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00014048
ITERATION	#95:	A=6018.73981	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00009372
ITERATION	#96:	A=6018.73986	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00006252
ITERATION	#97:	A=6018.73983	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00004171
ITERATION	#98:	A=6018.73985	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00002783
ITERATION	#99:	A=6018.73983	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00001856
ITERATION	#100:	A=6018.73984	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00001298
ITERATION	#101:	A=6018.73984	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00000826
ITERATION	#102:	A=6018.73984	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00000551
ITERATION	#103:	A=6018.73984	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00000368
ITERATION	#104:	A=6018.73984	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00000245
ITERATION	#105:	A=6018.73984	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00000164
ITERATION	#106:	A=6018.73984	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00000109
ITERATION	#107:	A=6018.73984	kn	Ecc=.72428	ω =225.00000	deg	✓[SUM (ERRORS) ²]=0000.00000073

CONVERGED SOLUTION: A=6018.73984 kn Ecc=.72428 I_o=0.00000 deg ω =225.00000 deg Ω =0.00000 deg
✓[SUM (ERRORS)²]=0.00000073



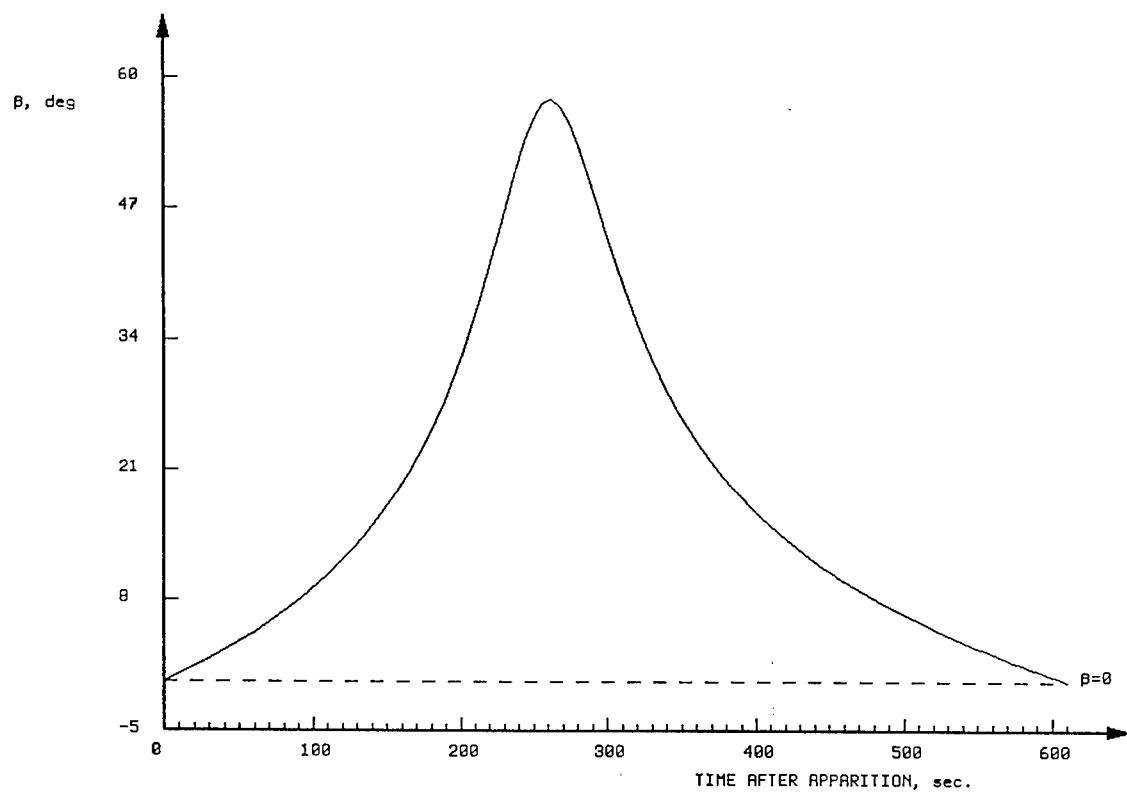


Figure 3. β versus time for the example from table 1 (satellite).

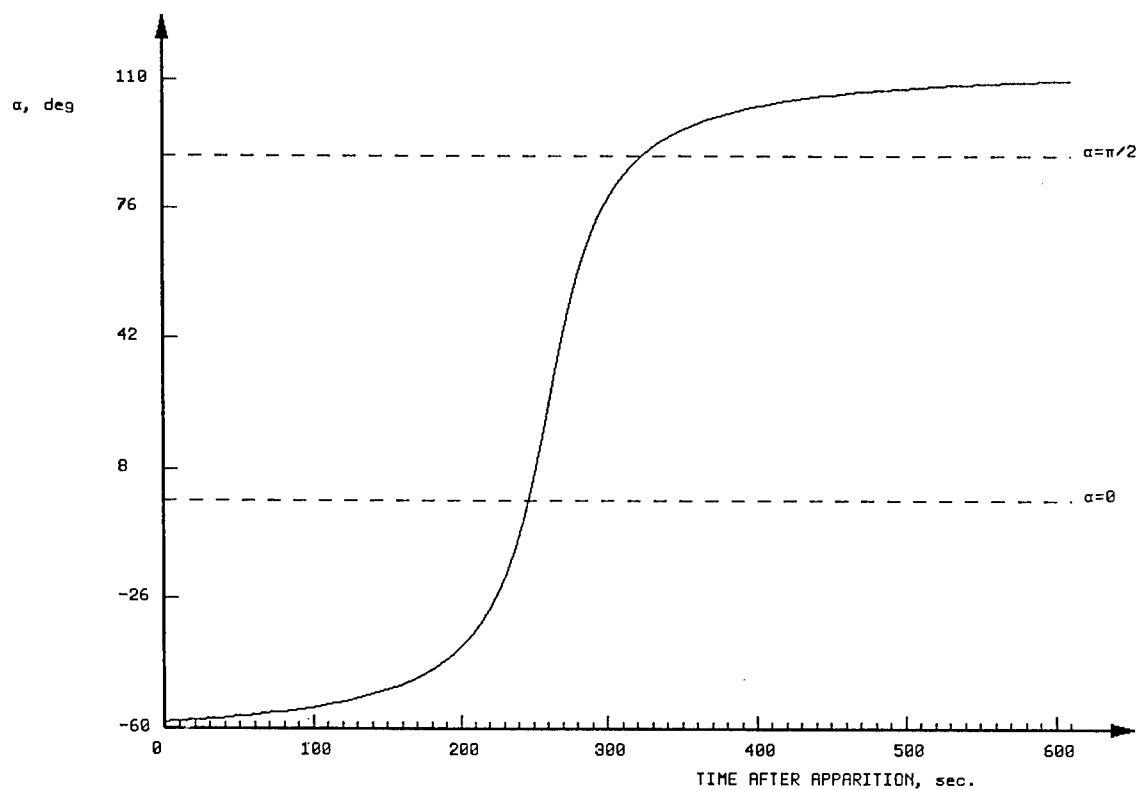


Figure 4. α versus time for the example from table 1 (satellite).

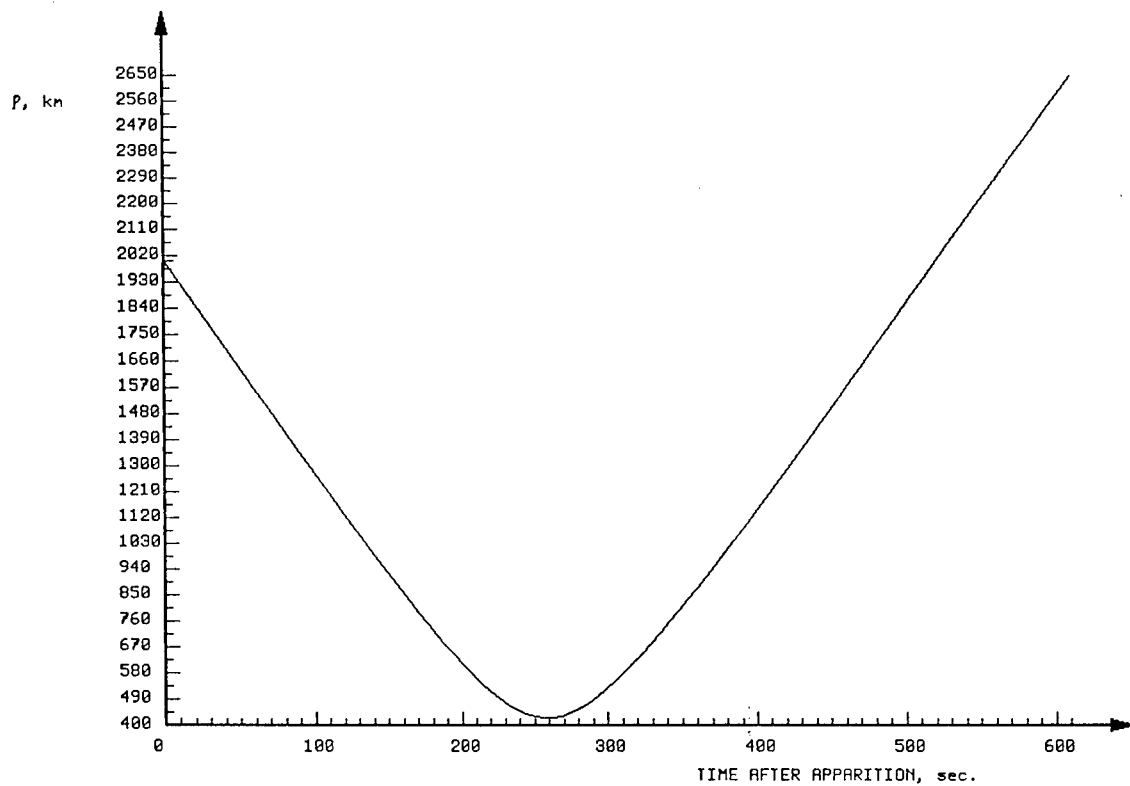


Figure 5. ρ versus time for the example from table 1 (satellite).

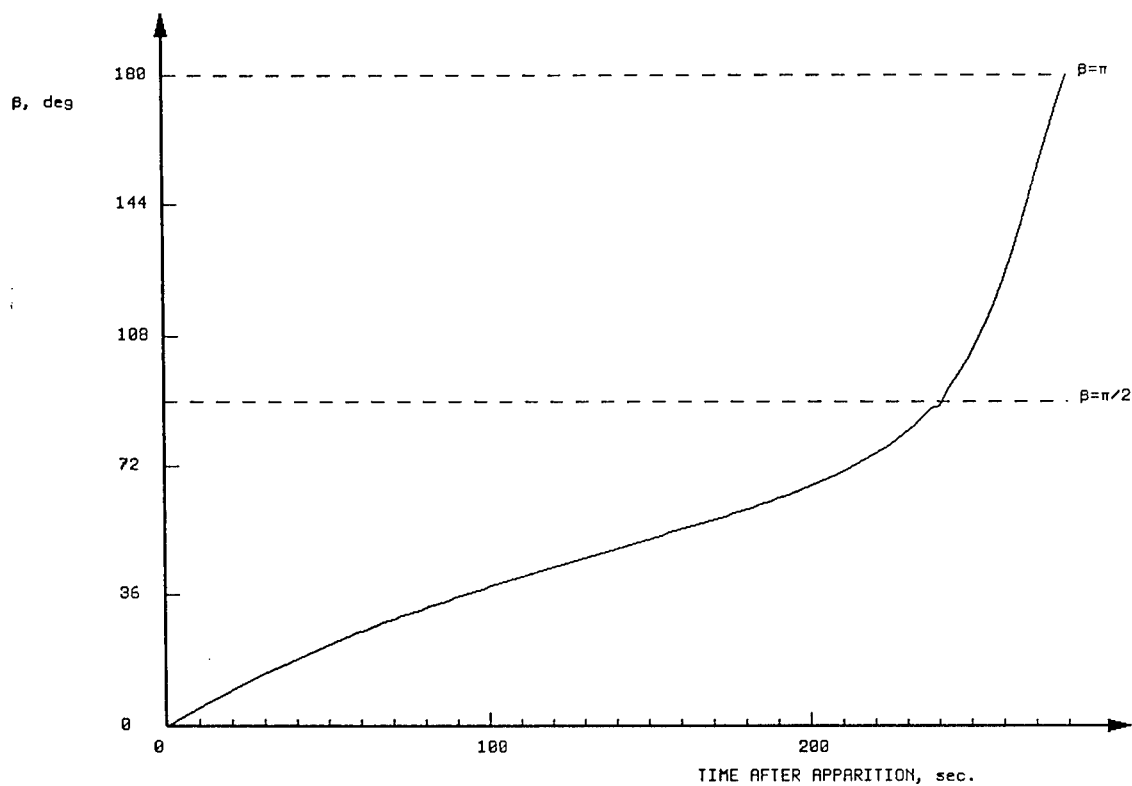


Figure 6. β versus time for the example from table 4 (ICBM).

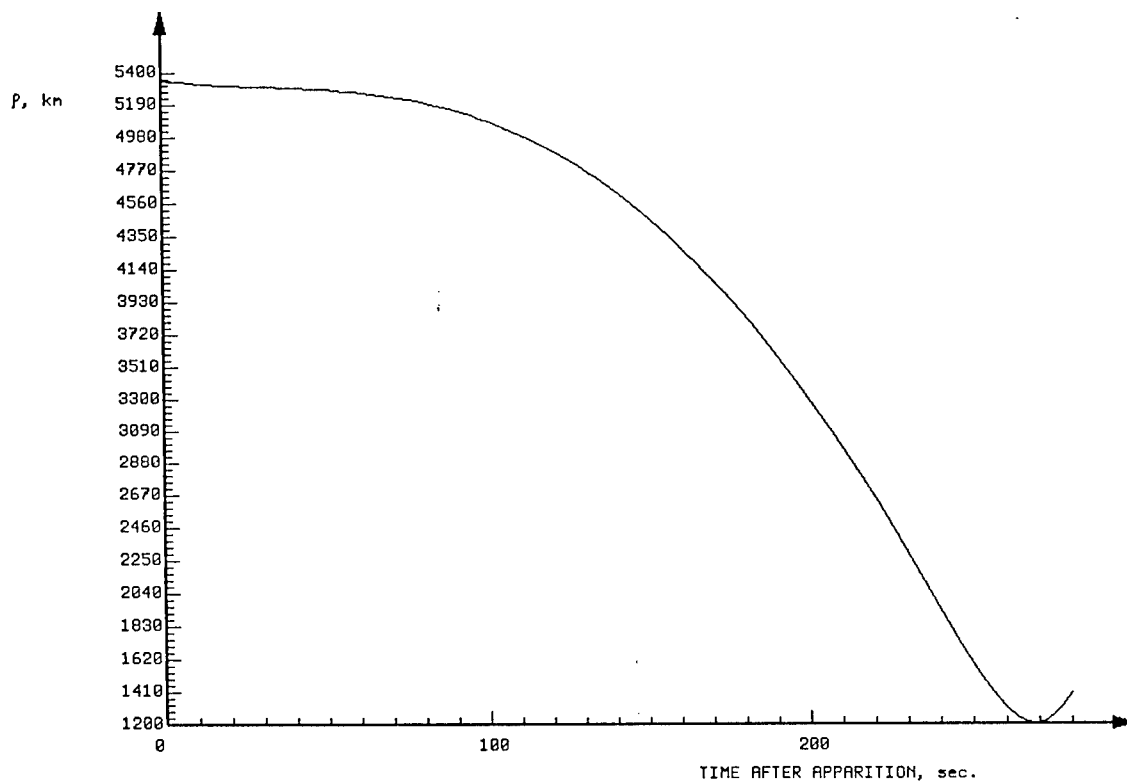


Figure 7. ρ versus time for the example from table 4 (ICBM).

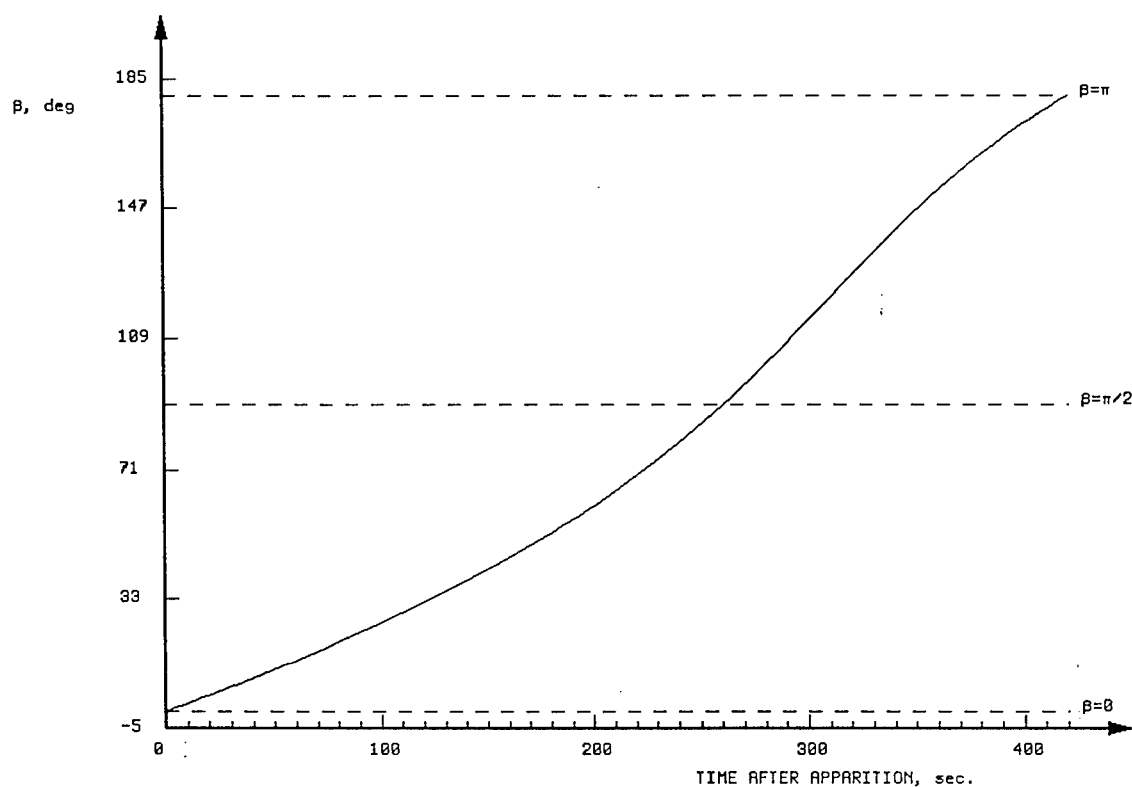


Figure 8. β versus time for 200 km range missile.

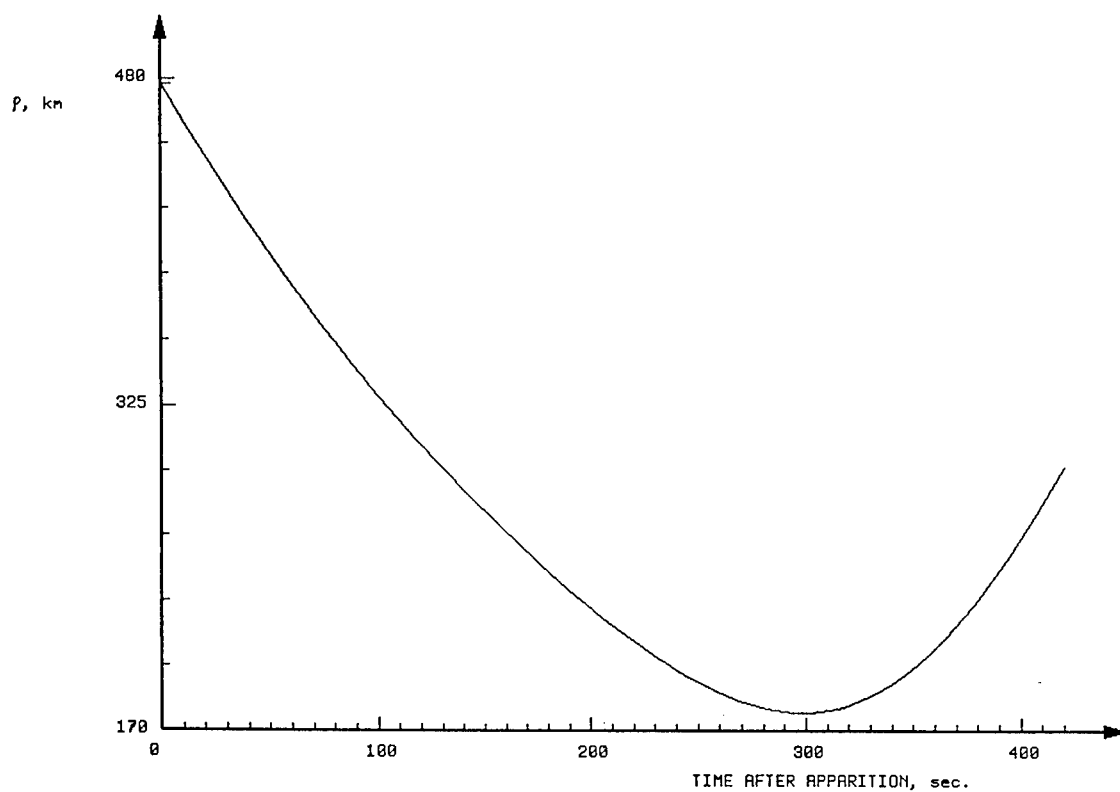


Figure 9. ρ versus time for 200 km range missile.

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2. McCuskey, S.W.: "Introduction to Celestial Mechanics," Addison-Wesley Publishing Co., Reading, Mass., 1963.

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